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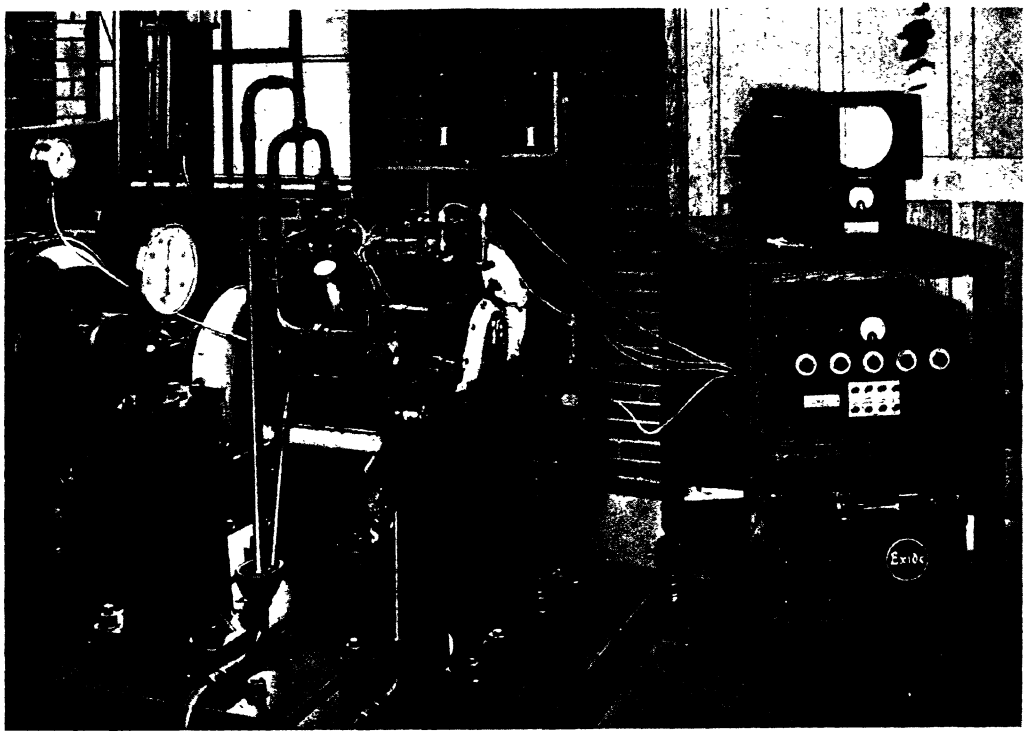
# THE CATHODE RAY OSCILLOGRAPH IN INDUSTRY

*By the Same Author*

THE CALCULATION AND DESIGN OF ELECTRICAL APPARATUS. (*Chapman and Hall.*)
ELECTRIC CONTROL GEAR & INDUSTRIAL ELECTRIFICATION. (*Oxford University Press.*)
SMALL ELECTRIC GENERATING SETS. (*Benn.*)
ELECTRIFICATION OF INDUSTRY *in the* ENCYCLOPEDIA BRITANNICA, ETC.



Complete Set-up of Standard Sunbury Indicating Equipment.
(*Courtesy Standard Telephones & Cables Ltd.*).

*Frontispiece.*

# THE CATHODE RAY OSCILLOGRAPH IN INDUSTRY

*By*

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# AUTHOR'S PREFACE TO SECOND EDITION

The phenomenal progress in design and application achieved by the cathode ray oscillograph has created a demand for information regarding the tube itself, its characteristics and its utilisation. In endeavouring to meet this demand, the author has kept two main purposes in view : first, to include all kinds of tube that are of use in industry, and secondly, to bear in mind throughout the interests of the user. Since the scope is restricted to the needs of industry, television tubes, which present their own problems and form a distinct branch of the subject, have not been covered.

There has been a tendency in the past to separate the glass and metal types of tube into watertight compartments, with the result that the latter model is frequently ignored altogether. But in spite of the difference in material and in evacuating practice, the two are essentially the same apparatus, and, moreover, their functions definitely overlap. In both design and application the one type can shed light upon the other ; while their relative advantages under the various operating conditions ought to be fully known in order that the best method may be adopted for each set of requirements.

In catering especially for the needs of the user, the author has provided a description of the various kinds of tube with which tests can be conducted at the present time and in the immediate future ; but has omitted historical matter which can only be of importance to purely theoretical readers. Similarly, little attention has been given to higher mathematics designed to indicate the practicability of the tube in the first place, and upon the derivation of its constants. These omissions have enabled a correspondingly larger amount of space to be allocated to the more practical side of the subject, of which three aspects have been kept specially in view.

First, it is necessary that the worker shall thoroughly understand his instrument ; and the opening chapters are accordingly devoted to a description of the components that go to make up the modern cathode oscillograph, their functions, alternative forms, and individual characteristics. Secondly, the performance of which the pieces of apparatus so constituted are capable is deduced, and the various kinds of test and observation are defined. Thirdly, practical examples are given of each class of test, with records derived from actual industrial applications. These instances naturally cover a wide range of work and include many branches of engineering ; but are really of general interest, since the principles and methods involved are in nearly every case available in other fields than those to which they have been actually applied.

A brief reference may be made to the two final chapters, which are somewhat unusual features in a work on the present subject. As regards Chapter XI, the electron microscope and diffraction camera are cathode ray tubes, the development of which has gone hand-in-hand with that of the oscillograph tube proper. They are based upon the same principles as have been set out in the first three chapters, and apart from the fact that their images are not called upon to " oscillate," and the focussing principle may be more highly elaborated, they are virtually the same instrument. Their appearance in the scientific world has been so recent and their performance is of such far-reaching importance that no apology is made for their inclusion.

The last chapter deals with construction, operation and maintenance, the first of which has been included for two main reasons. While it is recognised that few users will desire to make their complete apparatus, the ability to execute repairs or even modifications may be required at any time. Secondly, there is a close resemblance between the glass tube " set " and the wireless receiver, and it is all to the good that the class of experimenter who enjoys making up the latter shall be encouraged to do the same with the oscillograph, the entertainment value of which should in any event transcend that of the harmonograph and similar amateur-built apparatus.

Advantage has been taken of the new edition to replace some seven illustrations with more effective ones, and to add about forty new figures, with accompanying letterpress. More details have been shown of the construction of typical oscillographs, such as the large metal tube type, the Restriking Voltage Indicator, and the small portable model. New types described for the first time are the miniature " Miniscope " set, the robust 6 in. screen tube, and the " Magic Eye," while typical applications of the latter, and of the standard glass tube used as a galvanometer, have been described. Other subjects now introduced include the electronic switch for giving two or more records with a single tube, the cathode ray fault-finder, steel sorting apparatus, strain gauge, the measurement of Young's modulus, and of noise and vibration, and the analysis of musical sounds. More details are given of echo-detection (which may now be called Radiolocation) ; and the extension of the principle to the detection of flaws in conductors by the aid of supersonic vibrations is described. The chapter on the Electron Microscope has been considerably amplified in order to include the most recent instruments and their achievements, and further practical information as to operation and use, such as the preparation and mounting of specimens, metallography, and characteristics of electron micrographs. Six additions have been made to the chapter on Construction, Operation and Maintenance, dealing with photographic methods and a few other practical details ; and a new section has been added to the Appendix, describing a convenient and portable lecture-demonstration outfit for the benefit of those who may desire to exhibit the capabilities of the cathode oscillograph to an audience.

Considerable portions of the text were given a preliminary trial in articles appearing chiefly in the *B.E.A.M.A. Journal*, and smaller extracts have appeared in the *Electrical Engineer and Merchandiser* (Australia) and the *N.Z. Electrical Journal*. Thanks are due to the Editors for permission to republish this matter in its revised form. Most of the oscillograms were taken in the Development Laboratory and other test-rooms of the General Electric Co. Ltd., at Witton and also at Coventry ; and owe much to the skill of Mr. G. L. G. Jeans, B.Sc., and other operators. Some of the most striking examples, however, were kindly provided by eminent research workers and institutions, and the author would especially express his thanks to the Electrical Research Association (Figs. 56, 103, 104, 107, 109, 120 and 122 to 127), Building Research Station (Fig. 148), National Physical Laboratory (Figs. 101, 171), Professor G. I. Finch, M.B.E., D.Sc., F.R.S. (Figs. 166, 168, 169), Professor F. C. Lindvall, Ph.D., M.A.I.E.E. (Fig. 93), and Mr. H. Cobden Turner, M.I.E.E. (Fig. 78) ; as well as to Messrs. Cossor (Figs. 146, 154, 155, 156), Salford Electrical Instruments Ltd. (Fig. 145) Cambridge Instrument Co. Ltd. (Fig. 50), Dumont Co. (Fig. 37), Henry Hughes Ltd. (Fig. 101 A and B), and the R.C.A. of America (Figs. 177 to 184). Illustrations of apparatus have been generously furnished by manufacturing firms to whom acknowledgment has been made in the text. Finally, he would like to express his indebtedness to Dr. W. B. Whitney, M.I.E.E., and many others who have assisted him with suggestions ; and to Mr. W. F. Baker, B.Sc., A.M.I.E.E., for his valuable help in preparing the diagrams for publication.

W. W.

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# SYMBOLS AND ABBREVIATIONS

A = ampere (amp.).
or = Angstrom unit ($10^{-4}\mu$ or $10^{-10}$ m.).
A.F. = audio frequency.
B = magnetic flux density.
B.E.A.I.R.A. (E.R.A.) = British Electrical and Allied Industries Research Association.
C = capacity (capacitance).
c/s. = cycles per second.
cm. = centimetre ($10^{-2}$ metre).
d. = diameter.
E = voltage (potential).
E.R.A. = Electric Research Association (see B.E.A.I.R.A.).
F. = farad.
f. = frequency.
GB. = grid bias.
H = magnetic field strength.
H.F. = high frequency.
H.T. (V.) = high tension (voltage).
$h, h_1, h_2$ = height.
I, i = current.
in. = inch (2·54 cm.).
K, k = constant.
kc/s. = kilocycles per second ($10^3$ c/s.).
km. = kilometre ($10^3$m.).
kV. = kilovolt ($10^3$V.).
kVA. = kilovolt-ampere ($10^3$VA.).
L = inductance.
L.F. = low frequency.
L.S. = loud speaker.
L.T. (V.) = low tension (voltage).
Mc/s. = megacycle per second ($10^6$ c/s.).
MVA. = megavolt-ampere ($10^6$ VA.).
m. = metre (39·37 inches).
mA. = milliampere ($10^{-3}$ A.).
mls. = miles.
mm. = millimetre ($10^{-3}$ m.).
ms. = millisecond ($10^{-3}$ s.).
$Px_1, Px_2$ = horizontal plates (deflectors).
$Py_1, Py_2$ = vertical plates (deflectors).
q. = quantity (of electricity).
R, r = resistance.
R.F. = radio frequency.
R.M.S. = root-mean-square.
R.P.M. = revolutions per minute.
S.W.G. = standard wire gauge.
s. (sec.) = second.

V. = volt.
VA. = volt-ampere.
W. = watt.
X = reactance.
Z = impedance.
$\phi$ = phase angle.
$\lambda$ = wave-length.
$\mu$ = micron ($10^{-6}$ m.).
$\mu$A = micro-ampere ($10^{-6}$ A.).
$\mu$F = microfarad ($10^{-6}$ F.).
$\mu$s = microsecond ($10^{-6}$ s.).
$\mu\mu$F = micro-microfarad ($10^{-12}$F.).
$\pi$ = 3·1416.

## CHAPTER ONE

# GENERAL PRINCIPLES AND DESIGN

There is no electrical instrument in use at the present time which is making such rapid progress, both as regards development and application in the industrial field, as the cathode ray oscillograph. Yet until quite recent years it was almost unknown outside the realms of pure physics, and was classed by engineers generally among the curious vacuum tubes and other intricate glassware associated with higher electricity. To-day its use has spread from electrical laboratories to factories manufacturing radio apparatus and those dealing with telephony and telegraphy, then to heavy electrical industries, and by a further step to light and heavy mechanical and civil engineering enterprises ; and finally to a host of industrial applications beyond the realm of engineering altogether. The number of those interested in the capabilities and possibilities of the instrument is therefore very large, and all of them can profit by a consideration of what it has done and can do, not only in their own particular field, but in others.

The author therefore proposes to describe in as practical a manner as possible the needs which have brought about the introduction of the cathode oscillograph, the principles underlying its operation, the methods whereby these principles have been embodied in its various forms, the many purposes to which it has been applied, and the advantages which have been responsible for the displacement or outdistancing of previous or competing methods and instruments.

**Transient Measurements.** The measurement of a varying voltage (or current) has been effected by methods which have successively improved as time went on and as the demands became increasingly stringent. It was first carried out many years ago by the observer taking readings at suitable intervals of time from an ordinary indicating meter. Great difficulty was, however, experienced in recording fluctuations taking less than, say, 40 seconds for each cycle. The graphic type of instrument was therefore designed, in which a stylus is mounted upon the pointer, imprinting its own record upon a moving strip or disc. With these meters the fluctuations of slowly varying quantities can be traced out, such as the daily load curve on a power station or an individual motor ; but there is too much inertia and friction in the moving parts for them to follow accurately such a sequence as, for example, the starting peaks of a small motor ; while the cyclic variation of an alternating current produces no appreciable impression upon the trace at all.

Now a means of determining the wave-forms of D.C. as well as A.C. generators was urgently needed. However light the recording instrument arm was made, such a task was far beyond its powers, and the problem was solved by employing a beam of light as the pointer, in the well-known electromagnetic oscillograph. The form due to Duddell is that most generally used, and consists of two very thin strips of phosphor bronze stretched in the air-gap of a powerful magnet, with the smallest practicable mirror fixed across the strips. It is common knowledge that this instrument did everything required for the frequencies met with in connection with dynamo electric machinery.

The demands were, however, still increasing, and it became evident that the capabilities of even this low-inertia instrument could be overtaxed. Difficulties began to arise at a frequency of about 1,000 cycles per second, and a still lighter moving system became essential. This was obtained by acting upon the beam itself, without the interposition of metal conductors and a mirror. Ordinary light cannot be so deflected, but by employing an electron beam, or so-called "cathode ray discharge," which consists of a stream of electrons and thus constitutes an electric current, the requirement is met. Such a beam is readily created in an evacuated tube, and although invisible to the human eye, it produces an intense image upon the photographic film, and can be made visible by allowing it to impinge upon a screen composed of a fluorescent material such as zinc sulphide. Thus the cathode ray oscillograph was evolved, which can record frequencies of over a million cycles per second, and may have a writing speed of more than 100 miles per second.

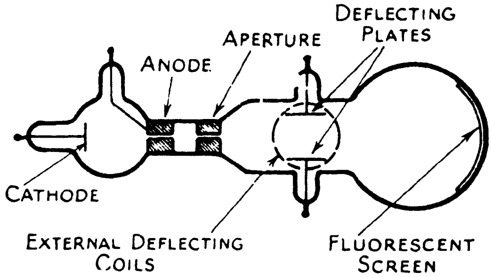

FIG. 1.—Sir J. J. Thomson's cathode ray tube.

In spite of its achievements and its rather academic name, the cathode ray oscillograph is in principle, and frequently also in practice, a simple piece of apparatus. The components that go to its making are all available in several alternative forms ; and as it is theoretically possible to associate any form of one with any alternative form of all the others, a great many different instruments can be produced, the characteristics of which can thus be varied over a wide range in order to suit a particular set of requirements. The author proposes to deal with each component separately, explaining its alternative forms and their respective advantages. Examples will then be given of complete modern instruments and of the work done by them.

The principles of the cathode ray oscillograph are essentially the same as those used by Sir J. J. Thomson in his epoch-making investigation on the properties of the electron. His tube, constructed in 1897, is shown in Fig. 1, in which it will be seen that he anticipated the features of the present-day instrument in a remarkable manner, including both electrostatic and electromagnetic methods of deflection. With this apparatus, values for the velocity and ratio of charge to mass of the electron were first obtained.

The instrument was applied to industrial testing in the same year by Professor F. Braun, though in a rather more rudimentary form than the foregoing. In his tube the screen end was given its present shape, increasing its suitability for accurate measurement.

The functions of the various parts can be readily understood from the description of the modern instrument which follows.

**Essential Components.** Cathode rays can be produced in an extremely simple manner. If an ordinary glass tube is fitted with two electrodes sealed through the glass and connected to a source of high potential, the character of the discharge inside the tube passes through a well-known series of changes as the air is exhausted from it. When the pressure has been reduced to about a millionth of an atmosphere, the last of the luminous striæ and the cathode glow have disappeared and the Crookes dark space has extended throughout the tube ; but the inside surface has begun to phosphoresce with a colour depending upon the composition of the glass. This phosphorescence is due to the impact of electrons emitted from the cathode, which constitute the cathode rays.

If the cathode consists of a flat disc at right angles to the axis of the tube, as was actually the case in the Thomson tube shown in Fig. 1, the rays will proceed down the tube in straight lines normal to the surface of the disc. They do not pass from cathode to anode as in the case of a true discharge, but continue until they strike an obstacle. If the latter is the anode, they will go past it when it is of smaller size than the cross-section of the rays, or through it if it is perforated. If the anode is situated in the side of the tube near the cathode, the rays will ignore it completely and go past until stopped by the glass or special screen at the far end.

Such a tube can be converted into a practical oscillograph by passing the rays through a small slit or other orifice near the anode in order to narrow the stream to the form of a stylus ; by providing a more efficient fluorescent screen than the plain glass surface ; and by arranging means for the deflection of the " pencil " by the voltage to be measured.

Since the cathode beam is actually a stream of negatively charged particles moving with a speed about one-tenth that of light, they can be repelled or attracted by a charged plate placed in the tube parallel to their course ; and, since a flow of electrons constitutes an electric current, the beam can be moved laterally by a current in a coil placed with its axis at right angles to that of the tube, or by a magnet in the same position. The deflection of the spot on the screen by the voltage can then be observed visually or photographed by means of an ordinary camera.

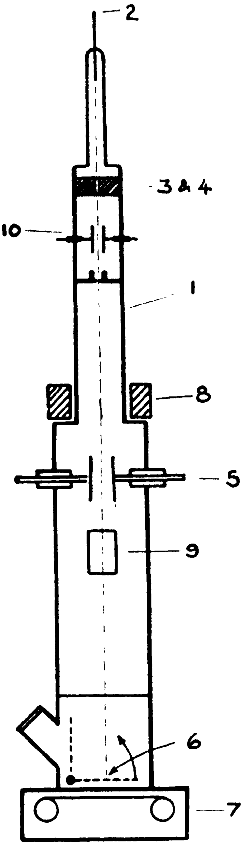

Fig. 2.—Typical cathode ray oscillograph.

A typical modern oscillograph is shown in the diagram forming Fig. 2, and will accordingly possess the following essential components :

1. TUBE OR ENVELOPE.
2. CATHODE.
3. ANODE.
4. APERTURE.
5. DEFLECTING PLATES OR COILS.
6. FLUORESCENT SCREEN.
7. CAMERA.

The shape of the envelope and the arrangement of the fluorescent screen and film holder in Fig. 2 are more characteristic of the metal than the glass type ; but as regards its broad outlines the figure may be taken as of general application. The camera is included as an essential component for an oscillograph, the last syllable of which signifies " write " ; although glass tubes are often used solely for observation purposes. The word " oscilloscope " is sometimes used for these models.

In practice, the aperture and the anode are combined and this perforated anode is called the " gun." The functions of the listed components are obvious, and they can be regarded as the basic requirements. But while this simple form will undoubtedly work, the truly wonderful results given by the modern cathode oscillograph are due to a number of additional devices which have increased its efficiency and convenience.

**Auxiliary Components.** The most important auxiliary requirements are given below.

8. FOCUSSING. As has already been explained, the cathode stream consists of negatively charged particles. Being similarly charged, they

repel one another; and although their high speed keeps them from diverging greatly from their original direction, the scattering becomes noticeable when the beam is restricted in size by passing through a very small aperture, especially when the tube is a long one. It is, moreover, advantageous to be able to adjust the degree of concentration in the same way as an image is focussed in the photographic camera.

9. TRAVERSING. As described, the oscillograph has no means for feeding the record in a direction at right angles to the deflection, a function that is carried out by the falling plate or rotating drum of the magnetic oscillograph. In this respect the cathode instrument is much the more flexible of the two, for not only can a rotating film or similar arrangement be employed, but instead the plate or film may be stationary and the spot itself traversed in the perpendicular direction.

10. TRAPPING. Before the test is made, or after it is over, the cathode spot should preferably not be left at rest upon the film or fluorescent screen, even in a position representing zero. On account of the very high intensity of the beam, at the best an unsightly patch of fog will be produced upon the photographic film, whilst at the worst the material of the screen will be destroyed at this point, or even the glass of the tube itself perforated. The beam is therefore frequently deflected into a " trap " when the tube is at rest, and " tripped " at the instant the record is required to start.

11. EXHAUSTING. Glass tubes are in general hermetically sealed with the required degree of vacuum already in existence. When, as is usually the case with metal tubes, the photographic plate or film has to be inserted inside the tube, release and restoration of the vacuum are required and a self-contained exhausting equipment must be provided.

12. VARIABLE LEAK. To secure the best results with a long cold cathode tube, the vacuum in the cathode discharge tube proper should be of a lower order than that in the main tube. A needle-valve or other device is then provided to permit a steady leak in the first tube, bringing its pressure up to the optimum value.

13. SPOT POSITIONING. A " zero adjustment " that is independent of the other controls forms a convenient addition.

14. GEISSLER TUBE. In order to check the vacuum during the process of exhaustion, a small glass tube, with electrodes, is connected pneumatically to the exhaust system. A discharge is passed through it from a trembler coil, and the appearance of the luminescence, notably the number of striæ, indicates when the correct degree of vacuum has been reached.

**Accessory Circuits.** The operation of the tube is controlled or facilitated by means of several accessory circuits, which are as follows:

(*a*) D.C. POWER SUPPLY. Energy is needed for the production of the beam, and frequently also for focussing and traversing; and is provided very much as in a wireless receiver.

(*b*) TIME BASE. For most purposes a horizontal traverse is required varying with time; and when a rotating drum or travelling film is not fitted, this is accomplished by means of a steadily rising or falling voltage applied to one pair of deflector plates.

(*c*) INDEPENDENT BASES. When the traverse is required to vary with some other quantity than time, the 50-cycle mains voltage is usually employed, and may be suitably modified for securing additional plainness and accuracy.

(*d*) VOLTAGE DIVISION (ATTENUATION). An adjustment is needed which will ensure that the record has a convenient amplitude with reference to the height of the screen or film. In such cases as lightning surges and short-circuit transients, the voltage to be measured is in general too high to be applied direct to the deflectors, and it is reduced by means of a voltage divider or potentiometer.

(*e*) AMPLIFICATION. The oscillograph is most frequently employed for recording extremely small voltages, and amplifiers are employed to enable both sets of plates to give a workable deflection.

(*f*) TIME MARKING. An exact time scale is often imprinted upon an oscillogram, especially when the base is not linear, by causing the spot to record a calibrated high-frequency wave upon the film.

**Advantages of the Cathode Oscillograph.** The principal features of the cathode instrument having now been mentioned, a few words may be said as to the advantages which it is able to offer. When the various applications are being considered in detail in later chapters, the respects in which the new method excels the one supplanted will be discussed in each case; but in this general and introductory survey it will be appropriate to compare the cathode instrument with its immediate predecessor, viz., the electromagnetic oscillograph. Its chief advantages on this basis are summarised below:

1. In its glass tube form, it is more robust, compact, and portable. There are no delicate mechanisms or suspensions, and no critical damping, to become damaged or get out of adjustment. Over-reading will not cause burning or overstrain. The metal tube form is even more robust, but because of its size and construction is not ordinarily adapted for portability.

2. It is much more convenient for visual determinations. The complete oscillogram can be observed and scrutinised in comfort upon a screen, the afterglow of which can render even low-frequency waves continuously visible, and transient waves measurable.

3. Its capabilities are considerably more flexible, affording facilities

for a much greater number of practical applications. For the magnetic oscillograph, only a linear time base is available for the longitudinal travel, provided mechanically by a rotating drum, moving film or (sub-linear only) falling plate ; while the cathode instrument can not only use these, but also linear and exponential bases derived from " sweep " circuits, as well as many other bases than time. In this way graphs may be recorded connecting almost any two quantities. Elliptical, circular, sine-wave, zigzag, and other bases can be employed that greatly increase the amount of information contained in a given oscillogram.

4. The range of frequencies and writing speeds is enormously extended, and at the same time distortion due to inertia and insufficient damping is avoided.

5. Use and adjustment are both more convenient. Focussing, extension of the scale in both the horizontal and vertical directions, horizontal and vertical positioning, alteration of the time-scale, and synchronising of the vertical deflection with the time base, are each effected by the simple turning of the appropriate knob.

6. The trace is as a rule sharper, finer and more uniform, especially with the metal tube type ; while both intensity and focus are readily adjusted.

7. Amplifying facilities bring about a greatly superior sensitivity.

8. The cathode instrument is typically cheaper and simpler, except as regards the very large continuously evacuated models.

9. The load taken from the circuit under test is almost zero, and there is thus no appreciable alteration in circuit-conditions due to the oscillograph.

In the next chapter the various components and their functioning will be described in detail, with the aid of typical examples of the complete instrument drawn from present-day practice.

## CHAPTER TWO

# DETAILED DESCRIPTION

**Typical Examples.** In order to exemplify the design and use of the various components, two typical oscillographs, representing as far as possible radically opposing practice, will be used for reference, and are shown in Figs. 3 and 4. These are respectively a glass-tube model, having a length of about 16 in. and a maximum diameter of 5¼ in.; and a metal tube continuously evacuated model, standing about 8 ft. high and recording on a high-speed film drum. The former is much used for the visual inspection of both transient and periodic phenomena, as well as for photographic recording when the writing speed of the transient phenomena is not very great; while the latter was designed for tracing very high-speed transients, or periodic phenomena with frequencies up to 100 or 200 kilocycles per second.

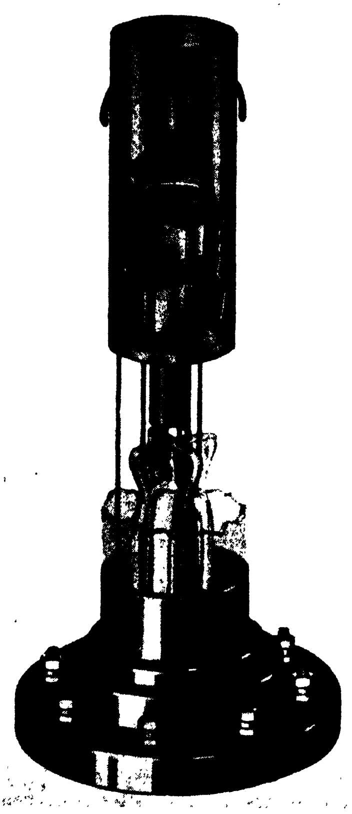

FIG. 3.—Typical glass tube cathode oscillograph (Cossor). The glass has been broken away to expose the internal arrangement. It is of cylindrical shape as far as the top of the figure, and then widens out into a conical extension.

## Description of Components.

1. *Tube or Envelope.* Two alternative materials are employed for the enclosure of a cathode oscillograph, namely glass or metal. Of these the former is cheap and is inherently insulating, while it is well adapted for retaining a high vacuum for an indefinite period. The metal tube is more robust and therefore more suitable for large models; necessary insulation being provided by porcelain bushings. It will be remembered that the same choice is available in the case of mercury arc rectifiers, and the same distinctions usually apply, namely that glass is used for the smaller

models which are kept permanently evacuated, while metal is used for the larger ones, which have a pumping equipment and are continuously exhausted ; although this distinction need not be a hard-and-fast one, as is evidenced by the recent introduction of permanently evacuated pumpless metal-enclosed mercury rectifiers. As regards size, again, the glass model described by Smith, Szegho, and Bradshaw,* which is 5 ft. long, is of interest.

As glass tubes are permanently sealed, it is not possible to make internal adjustments. Metal tubes possess a number of joints which have to be made airtight, viz., joints between sections of the envelope ; openings for various purposes, such as for the glass window near the base of Fig. 2, and for inserting the film ; and rotating joints such as operating spindles for adjusting the position of the deflecting plates and for winding the film. These joints are made with broad flanges or bushes, and are usually lagged with a special type of grease, that known as " Apiezon " being prepared for the purpose. A top view of a constructional flange is seen in Fig. 5 ; no bolts are required as the surfaces are held together by the air pressure. On account of the facility with which the metal tube can be refitted, its life may be said to be infinite ; whereas the life of a glass model is limited, being only a few hundred hours for the gas-focussed type and about eight to ten times as much for the high vacuum pattern.

The envelope of an oscillograph serves two purposes, namely the generation of the rays at the cathode end, and the enclosure of the beam throughout its length. Large continuously evacuated models actually consist of two separate tubes, viz., a small discharge tube (below 2 in Fig. 2), leading into the larger optical tube that supports the other components. The reason for separating these tubes is that optimum pressures are not the same for both. For example, with the largest models, having a cold cathode, the pressure in the small tube is about 0·1 mm. of mercury ; while in the large tube the value is less than 0·001 mm., otherwise the electron beam would experience too many collisions with other particles on its way down the tube. For smaller models, however, a compromise is usually effected, and there is only one tube. A hot cathode also renders the second tube unnecessary.

The chief object in using the continuously evacuated model is to enable the photographic film to be inserted inside the tube, where the beam can impinge directly upon its surface, with a consequent great gain in sensitivity.

2. *Cathode.* Two kinds of cathode are employed, namely the cold and the hot. A cold cathode consists of a metal electrode, which may be disc-shaped, spherical, or of other convenient shape, and is caused

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* See *Journal I.E.E.*, Vol. 75, 1934, p. 670.

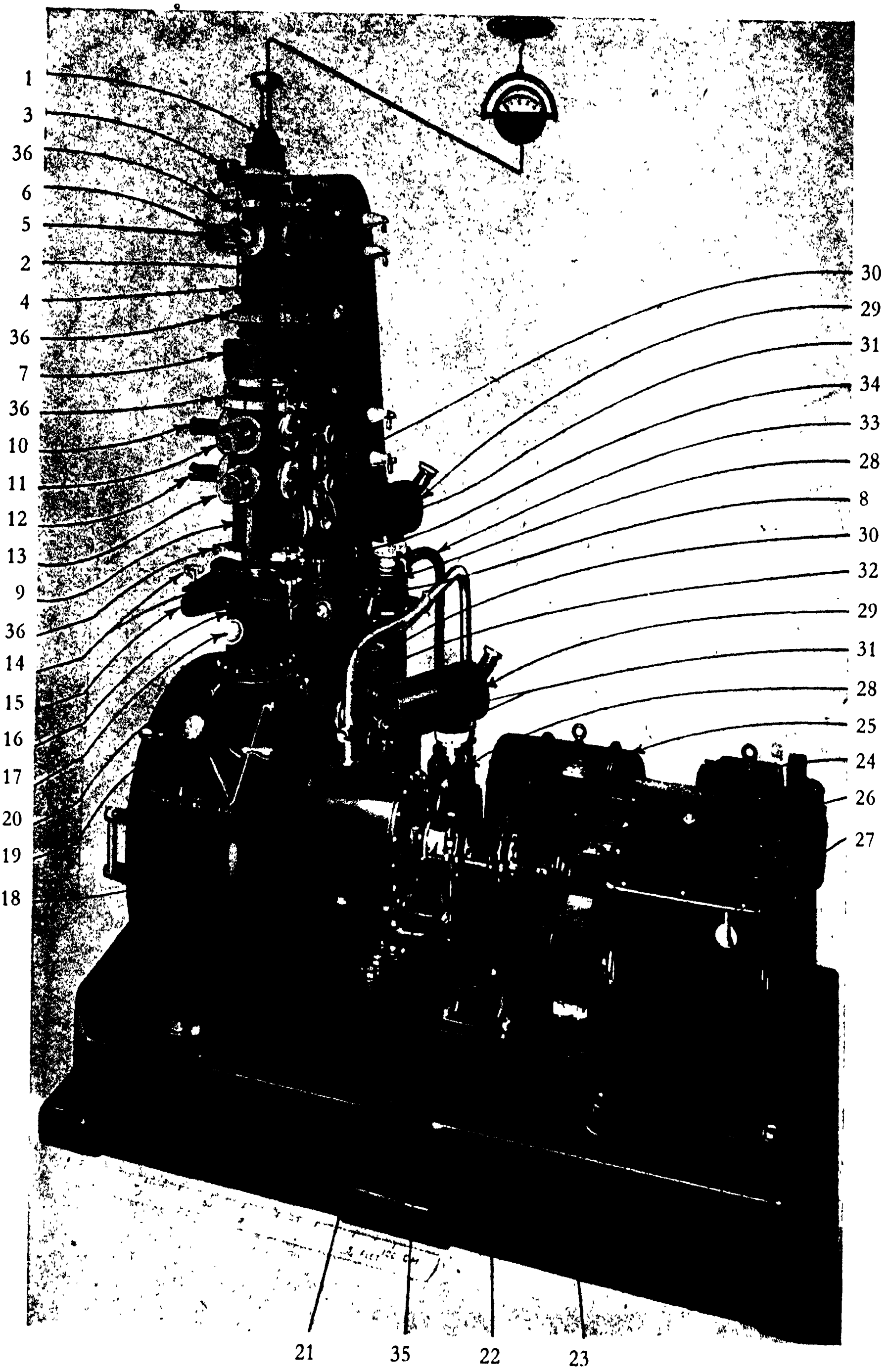

FIG. 4. Metal-tube cathode oscillograph (Cambridge), with film drum. (For key to references see page 11.)

## KEY TO REFERENCES IN FIG. 4.

1. Discharge tube.
2. Predeflection section.
3. Leak valve.
4. Leak valve control.
5. Untrapping plates.
6. Untrapping-plate feeders.
7. Concentrating coil.
8. Concentrating coil control resistance.
9. Deflection section.
10. Deflecting plates.
11. Deflecting-plate feeders.
12. Zero-shifting plates.
13. Zero-shifting plate feeders.
14. Oscillograph lifting screws.
15. Oscillograph lifting bracket.
16. Observation section.
17. Window.
18. Vacuum drum camera housing.
19. Camera loading aperture.
20. Shutter control.
21. Pin clutch.
22. Camera drive.
23. Layshaft.
24. Direct-current motor.
25. Synchronous motor.
26. Commutator housing.
27. Brush-lifting lever.
28. Diffusion pumps.
29. Mercury vapour traps.
30. Geissler tubes.
31. Vacuum release valves.
32. Gland exhaust pipe.
33. Backing vacuum pipes.
34. Vacuum test coil.
35. Pump water-cooling pipes.
36. Tube support brackets

to emit electrons owing to the application of high anode voltage. The hot cathode, on the other hand, is composed of a filament which is actually heated by the passage of an electric current, just as in the case of a thermionic valve. A typical example is a loop of tungsten wire having a symmetrical " V " shape, with a spot of barium oxide at the tip. The electron stream will then come from the oxide. This type of cathode enables very much lower voltages to be used, models being produced giving highly satisfactory results at 230 volts and even less.

As with thermionic valves, the cathode may be indirectly heated, a practice which possesses the same advantages as in their case. An example is seen in Fig. 10, where the heater is the only component that has not been sectioned. It is shown as a small white horizontal cylinder just to the left of the lead-in connections. The cathode fits closely round the heater, its upper half having actually been removed in the model. Shaped rather like a pistol cartridge, its flat end faces the aperture in the surrounding cylinder and is coated with the emitting oxide.

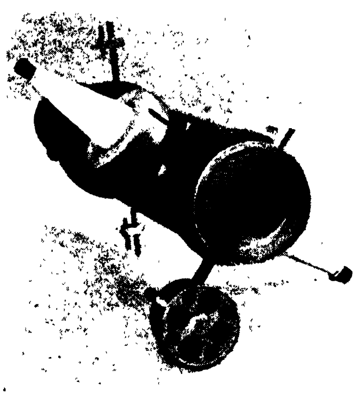

FIG. 5.—Pre-deflection section of Cambridge metal oscillograph showing variable leak.

The cold cathode may be pitted rather rapidly on account of the high voltage required, rendering periodical attention necessary. The long glass tube described in the paper referred to earlier has an interesting cathode composed of a $\frac{3}{4}$-in. aluminium ball, which is fitted loosely in a housing, and can hence be caused to move by tapping the outside of the tube, thus presenting fresh faces for the discharge.

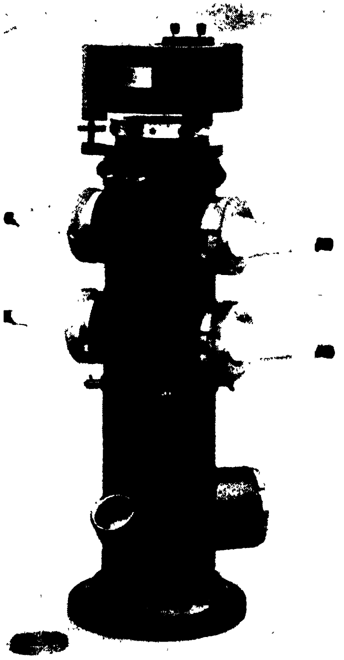

FIG. 6.—Deflection section of Cambridge oscillograph, showing focussing coil, and zero-shift and recording deflector bushes.

3 *and* 4. *Gun.* The anode and aperture combined is usually a flat plate forming a diaphragm pierced with a small hole having a diameter of say 0·5 mm., which gives the beam the desired cross section. In large oscillographs so much heat is developed at the anode that it requires water cooling, and it is then a rather complicated structure known as the " anode block." This is visible in Fig. 2, while the water-pipe connections can be seen coming from it at the near end of the tube in Fig. 5.

A somewhat different design is shown in Fig. 3, where in addition to the diaphragm pierced with the aperture there is a prolongation consisting of a cylindrical shield that actually encloses the deflector plates. This screen confers the advantage that the beam is much less affected by stray fields ; and further that nearly all the return current corresponding to that passing in the electron stream now goes direct to the screen instead of forming a space charge and thus greatly lowering the internal insulation resistance.

5. *Deflecting Means.* There are two methods of deflecting the beam, some reference to which has already been made. The most common

FIG. 7.—Deflecting, zero shift and trapping electrodes for Cambridge oscillograph.

device is by means of deflecting plates, which are used exclusively in all the models shown in Figs. 2, 3 and 4. In Fig. 2, three pairs of deflectors are illustrated at 5, 9 and 10 respectively, which are connected to their circuits with the aid of leading-in bushes of porcelain and are shown separately in Fig. 7. These deflectors can be seen at 10, 12 and 5 in Fig. 4, although the arrangement of 12 and its purpose are slightly different from those in Fig. 2. In Figs. 3 and 8 to 12, the deflectors are fixed to leads passing through the " pinch " of the tube.

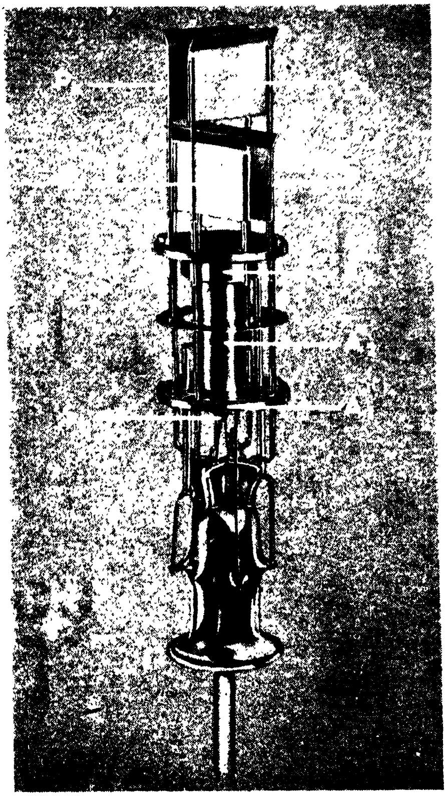

FIG. 8.—Gun structure of directly heated 3-anode high vacuum tube showing two pairs of deflector plates. Px, Py ; 3 anodes $A_1$, $A_2$, $A_3$, forming an electronic lens ; and the cathode shield Sh (see Fig. 15A) (Cossor).

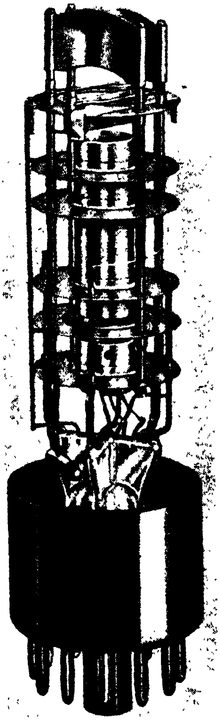

FIG. 9.—Interior of double beam (Cossor) high vacuum glass oscillograph showing electron lens. The double deflecting plates are the lower set immediately above the cylinder.

The second method is by means of an external pair of coils, one at either end of a horizontal axis, creating an electromagnetic flux which can deflect the beam functioning as a conductor carrying an electric current. This method can also be used for adjusting the position of the spot, four small solenoids being mounted round the outside of the tube, connected together in pairs, having a rheostat in series with each pair. The electromagnetic method is employed as one of two deflecting means when it is important to reduce interaction between the two deflecting fields to a minimum. Coil deflection is also frequently useful for the superposition of two signals, by electrostatic and electromagnetic means simultaneously ; for example, a timing pulse or wave may be applied by the coils, while the plates are responsible for the main deflection. Since the coils are external, they can easily be changed to suit individual requirements ; while they possess advantages when

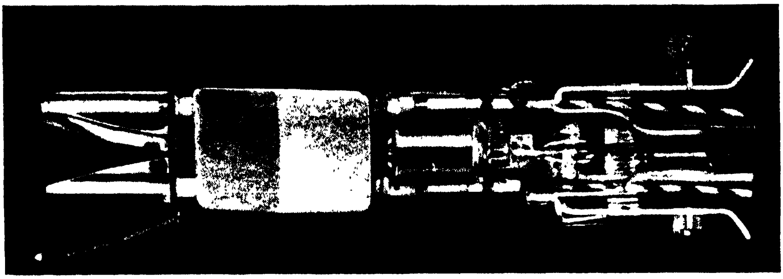

FIG. 10.—Section of 6 in. screen type 4201 CR tube (G.E.C.) designed for withstanding shocks.

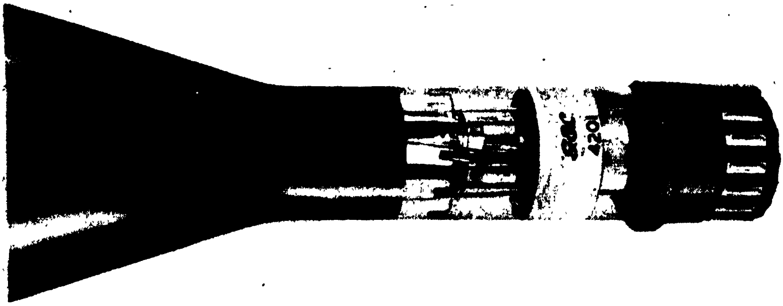

FIG. 11.—External view of Type 4201 tube.

a deflection is to be produced by a current. On the other hand, their presence renders screening by means of an enclosure of high-permeability steel somewhat more difficult.

Deflectors for a high vacuum glass tube are shown in Fig. 8, where the shape is somewhat different from that in Fig. 3, partly through the splaying of the gap to permit the beam being bent through a greater angle. The interior of a double-beam tube is shown in Fig. 9, the lower deflectors, situated just below the top disc, being duplicated by the interposition of a common electrode between the outer pair.

A specially robust design is employed in the G.E.C. type 4201 tube which is illustrated in section form in Fig. 10. For this photograph the whole assembly of electrodes was cut in half. All are designed to resist shock, and are supported on four strong rods of ceramic material. The deflectors, as shown by the edge-view at the left, are box-shaped, their external appearance being given by the adjacent PY plate to the right. It will be noticed that not only are the deflectors splayed considerably, but the inclination is increased half-way along the face, which is bent to an angle of about 15 degrees. Hence a wide angle of deflection is secured, combined with the maximum of sensitivity and economy of tube-length. The whole tube, which possesses a 6-in. fluorescent screen, is shown in Fig. 11.

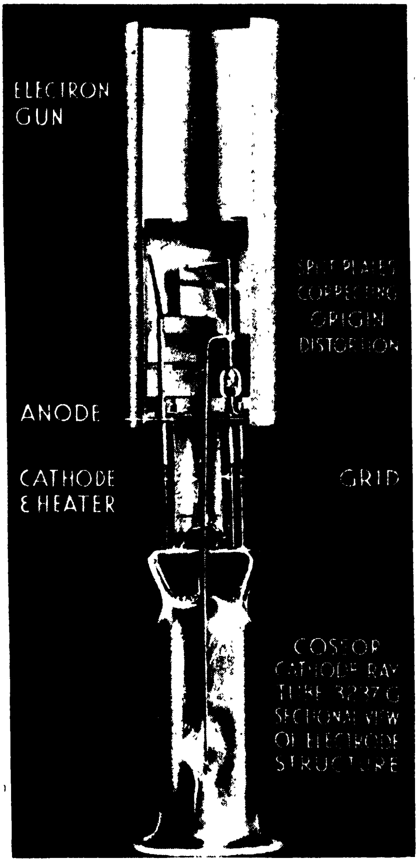
ELECTRON GUN
SPLIT PLATES CORRECTING ORIGIN DISTORTION
ANODE
CATHODE & HEATER
GRID
COSSOR CATHODE RAY TUBE 3237 G SECTIONAL VIEW OF ELECTRODE STRUCTURE

FIG. 12.—Interior of Cossor glass gas-focussed oscillograph. The deflectors are of the split type to obviate origin distortion.

Sometimes also one of each pair of plates in a gas-focussed tube is split as in Fig. 12, and a voltage difference maintained between them, to obviate "origin distortion." This is caused by the sensitivity becoming lower when the voltage between the plates is close to zero, through positive ions due to the gas partly neutralising the deflecting field ; and the effect is countered by the presence of the electrical field between the halves of the split deflectors, as described later on p. 51.

As described above, the deflectors are generally used to produce movement parallel to two axes at right angles to each other, and thus give Cartesian diagrams. In some cases, however, polar diagrams are more convenient, and can be traced by a modified form of tube. For this the usual deflectors are employed to provide a circular movement of the spot, very much as described later on p. 41, and radial deflectors are added, in the form of an axial conductor surrounded by a concentric electrode, consisting as a rule of a conducting layer deposited on the inside surface of the tube.

The common and most convenient practice of taking the deflector leads through the " pinch " of the tube introduces a small capacity between all of them, which in infrequent cases may be disadvantageous through causing cross-coupling between the two circuits, or through bringing the two sets of connections unduly close together. Some cathode ray tubes are made with the leads brought straight out through the glass at the neck, to meet such special conditions.

6. *Fluorescent Screen.* The fluorescent screen has been shown at the base of Fig. 2, and is there arranged to be pivoted out of the way when the camera is brought into use ; the screen being viewed by means of the inclined tube on the left. For the usual glass type of oscillograph, the screen is an essential feature for all purposes, and occupies the disc-shaped end of the tube. Its function is to render the beam visible, by giving out a brilliant spot of light when the cathode rays impinge upon it.

There are a number of substances which fluoresce under these conditions, differing among themselves in three main respects, namely, colour, afterglow (or memory), and luminous efficiency. An afterglow is advantageous for most purposes, since it gives time for the record to be scrutinised and even measured ; although it would be disadvantageous in the case of rapidly changing traces. The principal materials are :

(*a*) Zinc sulphide and zinc-cadmium sulphide, brilliant green colour with good afterglow, very suitable for visual inspection.

(*b*) Zinc silicate (Willemite), green colour with slight afterglow.

(*c*) Calcium tungstate, blue-violet colour very suitable for photography, no afterglow.

(*d*) Zinc phosphate, red colour with very long afterglow.

(*e*) Zinc sulphide with copper phosphorogen, blue colour with long green afterglow.

Of all available materials, the various mixtures of those listed under (*a*) can give the greatest brilliance for a given voltage. A wide variety of colours can be produced, with or without afterglow.

The standard screen material supplied for general purposes is Willemite, *i.e.*, screen (*b*). It is not easily damaged, especially as regards the effects of an over-bright spot. The brilliance due to a hot cathode with a maximum accelerating voltage of 1,100 in a high-vacuum tube is sufficient to enable the trace to be plainly seen in daylight. The colour is reasonably actinic for photographic purposes, and the afterglow just sufficient to obviate flickering for most 50-cycle applications.

When the utmost sensitivity is needed for photography, or when there must be a complete absence of afterglow, screen (*c*) is used, and a maximum anode voltage of 1,100 is still sufficient.

When, on the other hand, a long afterglow is required, screen (*d*) is employed; but to secure a brilliance equivalent to that given by the other materials, the anode voltage should be increased to about 3,000. Quite high photographic sensitivity is obtained if panchromatic plates or films are used. A good example of the advantages to be derived from this practice was given by Chapman,* in connection with an investigation of the rapid changes in the earth's electric field due to lightning. The camera shutter was arranged to be tripped by the lightning discharge itself, through the medium of a gas-filled relay, whereupon a second relay caused the film to be moved into position for a further record. It was inevitable that the exposure should be made subsequently to the flash, and the record therefore depended entirely on the afterglow.

By the method described, however, the shutter was operated before any substantial decay of the afterglow had taken place, and a satisfactory record was secured with a speed of $\frac{1}{25}$ sec., and an aperture of f/0.99 on hypersensitive panchromatic film; although a distinguishable record was also obtained at an aperture of f/6.3.

When transients have to be viewed, and also photographed upon a moving film, the requirements are at first sight contradictory. An afterglow is required for the first purpose, but if present for the second will cause blurring of the image and must therefore be avoided, as noted in connection with Fig. 122, Chapter VIII. The case arises in connection with the Cossor-Robertson electro-cardiograph, where it has been successfully dealt with by means of screen (*e*), which is really a variety of (*a*). As the negative paper employed is insensitive to green, the afterglow does not affect the photographic image.

Great activity is taking place in connection with this subject at the present time, and improvements are constantly being effected. For further information, the reader is referred to the paper by Levy and West before the I.E.E.†

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* See *Nature*, Vol. 131, 1933, p. 620.

† See *Journal I.E.E.*, Vol. 79, 1936, p. 11.

7. *Camera.* The photographic record of the oscillogram may be taken in three ways. With the glass type of oscillograph, the visible trace on the fluorescent screen is usually photographed by means of a lens camera ; and owing to the very short duration of the spot and its high writing speed, a high intensity and a good actinic colour (as given by screen (*c*) above) are of importance. Recurrent phenomena, which can be made to impress themselves upon the screen, say, fifty times in succession, give little difficulty, but for transient records it is usually necessary to employ an expensive lens having an aperture of f/1.9 or less, together with the fastest photographic films that can be obtained.

It will be realised that this method of recording the oscillogram is a roundabout one, and involves a number of losses and imperfections. It is therefore not surprising that when the speed of the spot is moderately high, the trace is apt to be somewhat blurred and to require a considerable amount of enlargement on account of the small scale on which the photograph must necessarily be taken. When very high writing speeds are involved, therefore, the second type of camera is used, shown in Figs. 2 and 4, whereby the plate or film is inserted inside the vacuum and is acted upon directly by the cathode rays. A very great increase in sensitivity is thereby produced, although a slow type of film is employed, having a speed of only about 20 H. and D. Since cathode rays do not penetrate the surface layer, there is very little to be gained by employing faster or thicker films.

The principal difficulty was originally the changing of the plate or film without requiring the vacuum to be released for each record : but there are now a number of designs whereby six or more photographs can be taken in succession and changed from outside the tube. The method indicated in Fig. 2 is to employ a roll film, very much like that fitted to the common hand camera, and operated by means of a turn-button passing through a greased bushing. A film drum is also frequently employed in which a continuous film is stretched round a polygonal support, each side of the polygon being brought into position in turn.

A third method has also been used to some extent with glass tubes, based on the Lenard window. For this, the end of the tube, normally occupied by the fluorescent tube, is replaced by a very thin aluminium or glass diaphragm supported mechanically by a metal grating. Such thin material permits a practicable proportion of the rays to pass through it, and the sensitive film is therefore placed in contact with the outside of the diaphragm.

A camera that has been specially designed for use with the glass tube is shown in Fig. 13. It is fitted with an f/1.9 lens, and a drum suitable for 35 mm. cine film driven by a 1/40 H.P. electric motor. Bromide paper can also be used, a grade being manufactured for use with the oscillograph with special sensitivity to the " blue " fluorescent screen. The drive is independent of perforations and will hence take the plain bromide strip, giving a smoother travel than is possible with a sprocket drum. Daylight loading is effected by means of removable cassettes, and there is a guillotine by which an exposed length of film may be cut off close to the driving roller and removed.

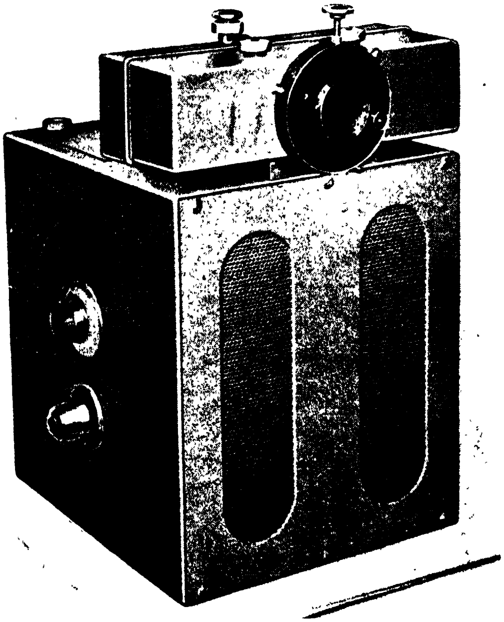


FIG. 13.—Cossor 35 mm. film camera for use with oscillograph (fixed focus).

8. *Focussing Means.* In the original cathode ray oscillograph the electrons moved at right angles to the flat cathode, and produced a moderately sharp spot on the screen, which was at no great distance from the cathode. To obtain a really satisfactory image, some method of concentrating them on the screen or plate is necessary, especially with long tubes. There are three methods whereby this can be done, and all are used in practice. The simplest is to insert a very small " residual " amount of gas, such as argon, in the tube, with the molecules of which the electrons collide in their path. Positive ions are driven out by the impact which move with a relatively low velocity and hence remain in the path of the beam. There is now an attraction

between these heavy ions and the electrons, and the beam is concentrated. The degree of focus can be adjusted by means of the cathode temperature, and for this reason a filament rheostat is an important adjunct to a gas-focussed oscillograph. Unfortunately, gas focussing fails as the writing speeds increase, since the positive ions tend to be left behind. The image of the spot begins to be blurred after a frequency of 25 kcs. per second has been exceeded, although individual designs can much improve upon this figure.

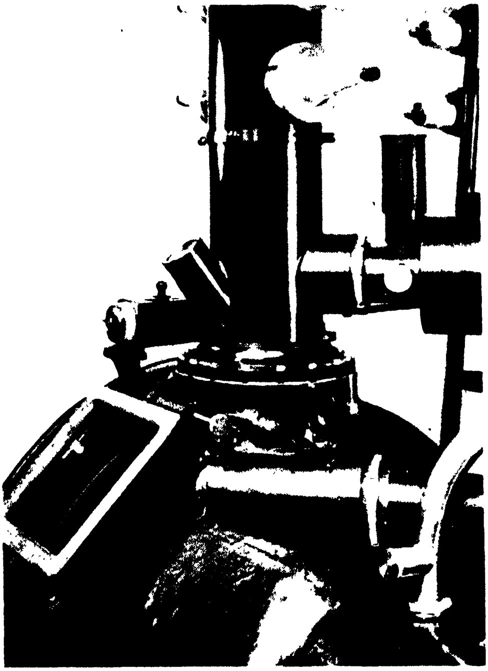


FIG. 14.—Loading aperture and controls of Cambridge oscillograph, showing focussing rheostat and Geissler tube.

The other two methods both employ the electronic equivalent of an optical lens, depending upon the creation of a flux that is able to refract the rays. Any flux, electromagnetic or electrostatic, that has axial symmetry, can act in this way.

For example, an axial magnetic flux can be formed by means of a coil enveloping the tube, as shown at 8 in Fig. 2, 7 in Fig. 4 and at the top of Fig. 6. The effect of this flux is that electrons which are moving outwards intersect the lines of force and are bent back again, but are given a helical path which does not interfere with their purpose. The focus is adjusted in this case by means of a variable resistance in series with the concentrating coil, seen mounted in front (*i.e.*, on the other side) of the metal tube and just above the film drum in Fig. 14. The position of the coil is adjusted by means of three micrometer screws upon which it rests, as shown in Fig. 6, these being necessary as the effective centre line of the coil may not pass through the geometrical centre.

Finally, the beam may be focussed by means of an electrostatic flux. Two examples are indicated in Fig. 15. In A, a cylindrical shield is shown enveloping the cathode, and maintained at a negative voltage of, say, 250 volts with respect to the latter. Equipotential surfaces are thus set up as shown in the figure, which are able to refract the beam and hence function as a condenser lens, producing the concentration of the beam shown. This shield can be seen just below the anode in Fig. 3, and surrounding the cathode (heater) in Fig. 10. Its effect is to make a much greater proportion of the rays pass through the aperture.

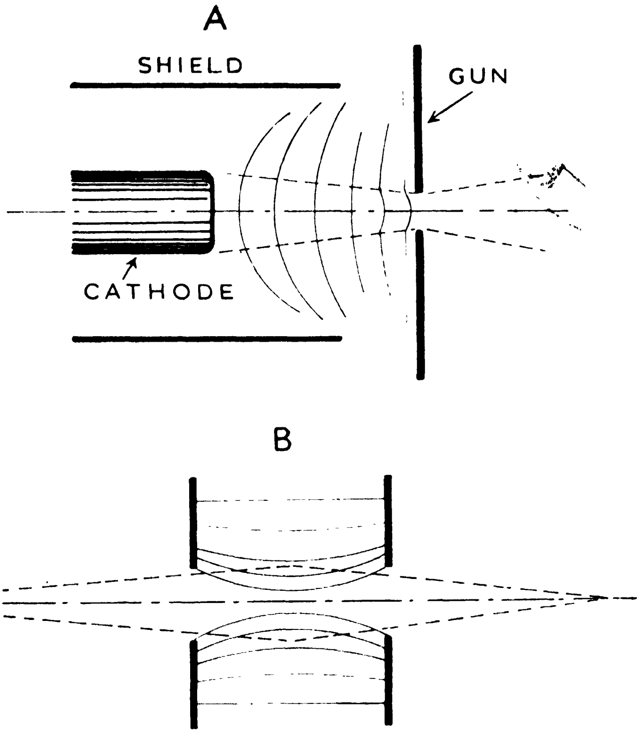


FIG. 15.—Electron lenses: (A) " condenser " effect of cathode shield ; (B) two-diaphragm focussing.

The utility of the shield has, however, been greatly extended by the provision of variable voltage, so that it constitutes an adjustable-focus condenser. By this means the brightness of the spot may be varied (or " modulated ") at will, from the maximum to a complete blackout. A control has thus been brought about which is exactly analogous to that effected by the grid in a triode valve, and hence the shield is frequently termed the " grid " or " modulator " of the oscillograph tube, and the shield voltage referred to as the " grid bias."

Many useful purposes are served by " grid " control. For example, it can form an alternative to trapping and untrapping for bringing the beam into existence. The bias is then adjusted so that the spot is just rendered invisible, and the pressing of a key, or even the arriving signal itself, suddenly increases the grid voltage and creates the beam in less than a microsecond. Automatic brightness control of the spot can be put into effect, whereby the intensity is increased in proportion to the writing speed, resulting in a more even luminosity of the trace. Other applications will be found later in the book.

On the other side of the gun, the rays may be focussed by the form of " lens " shown in B. Two diaphragms, each of which is pierced with a relatively large central hole, are maintained at differing voltages. The lines of force curve inwards from the edges of the aperture as shown in the figure, and a diverging beam of electrons is focussed thereby. This method, which is much used in high-voltage glass tube models, is illustrated in Fig. 8, showing the internal arrangements of the parts. Here the electron lens system possesses three components, of which A1 and A3 are diaphragms resembling Fig. 15, and there is a tube A2 between, but insulated from them. The voltages on the various elements are, in a typical case : cathode shield, — 120 volts ; cathode, 0 volts ; first diaphragm (A1), 250 volts ; tube (A2), 1,500 volts ; and second diaphragm (A3), 6,000 volts.

One great advantage of this method of focussing is that since all the different voltages are obtained quite simply from a power pack, or battery eliminator, no additional complication is involved thereby.

9. *Traversing of Spot.* So far, the oscillograph has been described as being capable of giving a deflection in response to changes of voltage applied to the deflecting means. This would enable it to act as a voltmeter ; but in order that a curve connecting two ordinates such as voltage and time may be traced out, means must be found for traversing the spot along the horizontal co-ordinate. The requirement can be fulfilled either mechanically or electrically.

First, the same general method may be employed as for the usual form of electromagnetic oscillograph, such as a drum round which is wrapped a sensitive film. This device is shown in the large model forming Fig. 4, where the drum is housed in the lower casing 18, and the film is inserted through the aperture 19 ; while an enlarged view, with the drum in position, is given in Fig. 14. In this instance the drum is driven by means of one or other of two geared motors (one synchronous and the other D.C.), through a stuffing gland which actually forms an evacuated chamber at an intermediate pressure ; although a more usual arrangement is to employ an induction motor with the squirrel-cage rotor inside the vacuum and surrounded by a thin extension of the enclosure, the stator being mounted concentrically outside this extension.

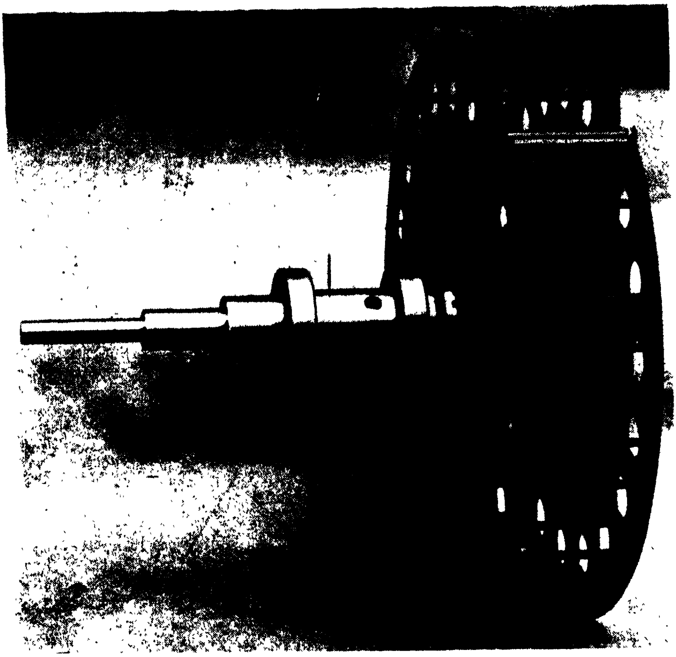


FIG. 16.—Drum camera rotor for Cambridge metal oscillograph.

In the present instance the drum has a circumference of 2 metres and rotates at a maximum speed of 3,000 r.p.m., which gives the film a traversing speed of almost exactly 4 miles a minute. A view of the drum is given in Fig. 16, showing the method of attaching the film by winding the ends on two small rollers. Whatever attachment is adopted must be extremely robust, and must ensure that as little of the record is lost at the join as possible. The use of a travelling cine film or paper has already been mentioned in connection with Fig. 13.

Alternatively, the spot may be traversed by the second deflecting means fitted to the tube in a plane at right angles to the first, such as the deflector plates 9 in Fig. 2, Px in Fig. 8, or the similar ones in Fig. 3.

This can be used directly for obtaining voltage-current curves, by connecting the latter deflectors to a non-inductive shunt through which the current passes; and other records can be obtained in a similar manner. But the majority of curves are required to a time base, and various circuits are therefore employed which will give a falling or a rising voltage, moving the spot across the screen at a predetermined rate. The design of these is given in the next chapter.

10. *Trapping.* The previous section will have indicated that for at any rate the large metal-tube instruments the spot requires to be released when the record is to be started. When at rest, the spot is "trapped," a function carried out in Fig. 2 by the upper deflector plates 10 deflecting the beam away from the aperture in the cup below the trap plates. This fulfils two purposes; in the first place the spot is ready to begin the record as soon as the sweep voltage is applied to the deflectors, and secondly, the spot is kept off the fluorescent screen. Some glass models are provided with a little metal pot fused into the screen near the periphery, into which the beam is deflected when at rest. It should be explained that the focus is liable to alter shortly after the beam is started, and it is the best practice to have it in being, correctly adjusted and focussed, in readiness for the taking of the record.

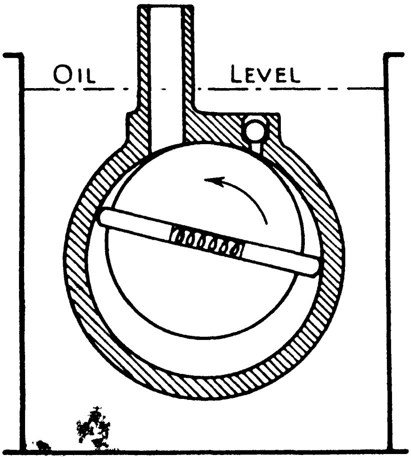


FIG. 17.—Mechanical air pump.

11. *Evacuating Equipment.* As has already been stated, the glass form of oscillograph is permanently evacuated and no further provision is required after it leaves the maker. The metal tube type, however, is provided with an exhausting equipment capable of producing a

vacuum as low as $10^{-5}$ mm. of mercury in about 20 minutes. Pumping plant has been greatly improved and simplified within recent years. For all metal tube oscillographs, two distinct stages of evacuation are used, namely a mechanical air pump, followed by a mercury or oil diffusion pump. A typical example of the former is given in Fig. 17, which is simply a rotary form of piston pump, so designed that the clearance in the " cylinder " with the " piston " at the beginning of its stroke is negligible. This pump can reduce the pressure from atmospheric down to about $10^{-2}$ mm. Hg. at the oscillograph for a single-stage pump as shown, or $10^{-4}$ mm. for a double-stage model.

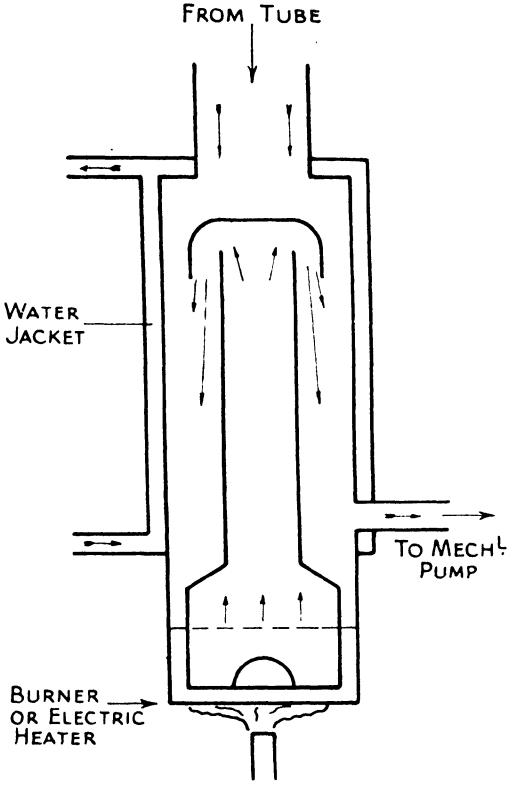


FIG. 18.—Diffusion pump.

The diffusion pump, which is shown diagrammatically in Fig. 18, is a remarkably simple piece of apparatus, consisting of a tubular vessel in which either mercury or a special hydro-carbon oil having a very low vapour pressure is boiled. The ascending vapour carries away the remaining air, which passes on to the mechanical pump ;

while the vapour is condensed and falls back into the boiling tube. A small self-contained pumping set is shown in Fig. 19 in which the diffusion pump is of glass and hence exhibits the internal construction. The mechanical pump is of a somewhat original design in that the rotating cylinder is pivoted at the centre of the fixed one, and thus revolves eccentrically to itself; while the single vane is located on the fixed cylinder, about midway between the inlet and outlet orifices.

Either gas or electricity may be employed for supplying the necessary heat. Two mercury diffusion pumps can be seen on the oscillograph in Fig. 4, one beside the main tube, and one above the main bearing for exhausting the intermediate chamber between the two bearing glands.

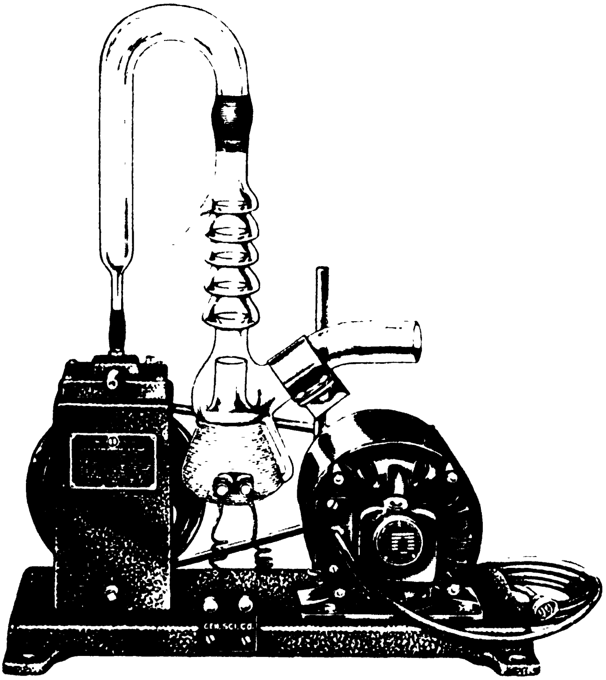


FIG. 19.—"Cenco" oil diffusion pumping set. (Central Scientific Co., Chicago.)

The chief advantage of the oil is its low vapour pressure of less than $10^{-6}$ mm. at normal temperature, as compared with about $10^{-3}$ mm. in the case of mercury. Cold vapour traps (29 in Fig. 4), usually packed with solid $CO_2$ and ether, are essential between the oscillograph tube and diffusion pump when mercury is employed, but are unnecessary when oil is substituted. Their chief drawback is a considerable reduction in pumping speed.

12. *Variable Leak.* In order to provide the lower degree of vacuum for the small discharge tube of cold cathode metal tube instruments, a variable leak is provided which permits a steady ingress of air to take place, and this is regulated at such a value that the milliammeter connected to the cathode shows a reading of between 1 and 1·5 mA.

The design of a variable leak is simpler than would have been supposed, since at such low pressures the air is very sluggish ; and for the instruments shown in Figs. 2 and 4, a $\frac{3}{16}$-in. tube provided with a needle-valve would give satisfactory results. The model in the second of these figures employs an ingenious type of leak, shown in Fig. 20, in which the air passes through a disc of porous china that is more or less immersed below mercury. An external view of the leak is shown in the upper part of the pre-deflection section of the Cambridge oscillograph in Fig. 5, where the tube is resting on a projecting drum-shaped enclosure surmounted by a gear-wheel. By means of the small pinion, the diaphragm containing the porous disc is rotated and effects its regulation.

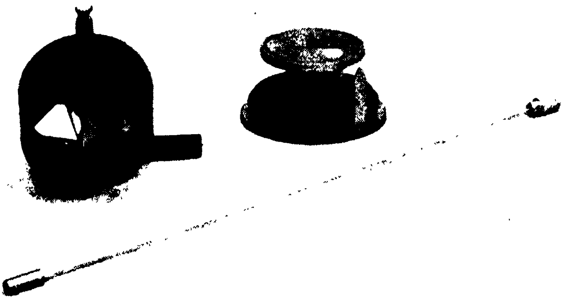


FIG. 20.—Porous diaphragm type of air leak.

13. *Positioning of Spot.* The position of the beam can be adjusted for the metal tube by various means, one of which was indicated in connection with " Deflecting Means " in section 5 above, wherein four deflecting coils had their relative strengths varied by means of rheostats. In Fig. 4 there is an additional set of deflecting plates 12, across which a variable voltage from a conveniently placed potentiometer rheostat can be impressed. A further method consists of employing a permanent magnet fixed to the tube in such a way that one pole

can be moved relatively to the beam and can afford the desired adjustment. Two such magnets can be seen attached to a cross-arm at the far end of the tube in Fig. 5.

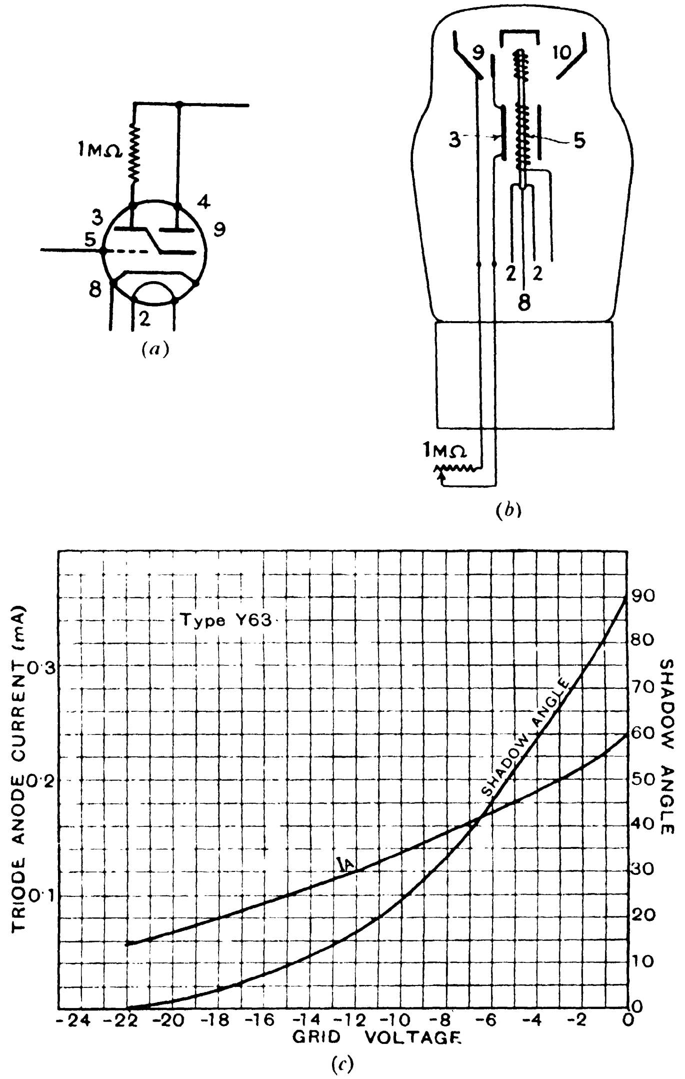
For the glass tube, where space does not in general permit the use of auxiliary deflectors, the voltage of the existing plates, in the case of electrostatic deflection, is raised or lowered by means of a potentiometer supplied with D.C. voltage from the power unit. The slider is connected to one plate, and the ends of the resistance are maintained at positive and negative potentials respectively with regard to the mid point, which is earthed and therefore at anode potential. When connections are brought out from all four plates, the potentiometers for vertical and horizontal shift are connected to the two " free " plates, *i.e.*, those that do not go to the work or time base voltage and are shown earthed in the usual diagram ; but when these two plates are joined together inside the tube, the shift voltages have to be applied to the other plates. Leads are taken from the sliders through resistances direct to the plates, while the work and base voltages are connected to the plates through condensers.

When electromagnetic deflection is used, an adjustable direct current is passed through the deflecting coils in parallel with the work current, a choke being interposed in the D.C. circuit to prevent the A.C. from being diverted.

14. *Geissler Tube.* The monitor vacuum tube is a much simpler device than its usual name would suggest. It consists as a rule of a plain glass tube about 4 in. long and $\frac{3}{8}$ in. in diameter, with wire electrodes fused through the ends. In practice it is mounted in a protecting cylindrical enclosure on the exhaust pipe, with which it communicates, just where the pipe leaves the main oscillograph tube ; and may be seen in this position in Fig. 4 near the right-hand margin, immediately to the left of the vapour trap cylinder. A high tension discharge from an induction coil of the automobile trembler type is passed between the electrodes, and the degree of vacuum attained at any stage in the pumping process is indicated by the appearance of the familiar striæ and dark spaces.

It will be remembered that the cathode rays are formed when the Crookes dark space has spread throughout the vacuum tube ; and the pumps are therefore operated until a complete blackout occurs in the monitor tube. The high tension supply is then switched on to the cathode, and the vacuum in the discharge tube relaxed by means of the air-leak until the milliammeter in the cathode circuit records a H.T. current of 1 to 1·5 mA., which is kept constant while the oscillograph is in use. It will thus be seen that the Geissler tube functions as the indicator for the coarse adjustment, and the milliammeter for the fine.

MAGIC EYE. A much simpler form of cathode ray tube than any that have been illustrated in this chapter is in wide use under the name of the " Magic Eye." Although it is of only the size of a standard small radio valve, it incorporates an amplifying triode in the same bulb, and forms a sensitive detector and measuring device for a number of purposes.



(a)

(b)

(c)

FIG. 21.—Magic Eye. (a) General scheme. (b) Arrangement of electrode in Osram Y63. (c) Characteristic curves of (b).

The principle and arrangement of the tube are illustrated in Fig. 21 (*a*, *b*, *c*), in which the left-hand diagram shows the general scheme and that on the right gives the actual design in the case of the Osram " Tuneray," so-called because it is most used for indicating when a wireless set is exactly in tune. Of the various electrodes, the indirectly heated cathode (8) is common to both triode and cathode ray tube. The former will be easily recognised as possessing the usual three electrodes (3, 5, 8) ; but the latter is rather different from the more familiar cathode oscilloscope.

First, the anode (4) is in the form of an annular hollow cone, the inner surface of which faces the end of the bulb and is coated with fluorescent material, so that it also forms a target or screen. When, therefore, the cathode is heated and the specified voltage of 250 applied between anode and cathode, a stream of electrons flows from the part of the cathode within the target to the inner surface of the latter, causing the fluorescent material on that surface to glow. In the absence of any other agency, a continuous ring of light would be seen at the end of the tube.

Projecting through the target, however, is a single deflector (9) in the form of a short rod, forming a continuation of the triode plate. Its voltage is equal to that of the target (250 v.) less the voltage drop in the resistance (1MΩ) due to the anode current in the triode. When no voltage is applied to the grid, the deflector is at a lower potential than that of the space in its vicinity, and therefore carries a negative charge which repels the electron stream and produces a " shadow " sector of about 90° in width, the deflector thus functioning as a control electrode. When a small negative voltage is connected to the grid, the anode current decreases, causing the deflector voltage to rise, and the width of the shadow sector is reduced. A voltage of about — 22 is required to cancel the shadow altogether.

The variation of shadow angle and anode current for varying grid voltage is shown for an average tube by the curves in Fig. 21. Overloading, *i.e.*, the application of more than — 22 volts to the grid, causes an extremely bright sector to replace the shadow, owing to the control electrode now becoming positive and attracting more than the normal quantity of electrons to its side of the target. It should be noted that the triode is designed with a " variable-mu " characteristic—*i.e.*, while being sensitive to weak signals, it requires an unusually strong one to overload it.

The Magic Eye forms a very neat and cheap detector, which can serve also as a measuring device when only approximate indications are required. Adjustment of the shadow angle can be effected by varying the resistance of about a megohm connected between the control electrode and the final anode, the shadow contracting with decreasing resistance.

Some patterns of the tube are made with more than one control electrode, an example by Messrs. Mullard (Type E. M. 1) having as many as four. These give rise to four equally spaced shadow sectors, all of which expand and contract together, and produce a more noticeable indication.

## CHAPTER THREE

# ACCESSORY CIRCUITS

It is very seldom that a cathode ray tube is used by itself, *i.e.*, without being incorporated in a " set " along with associated equipment. In any event, an " accelerating " voltage connected between anode and cathode is always essential, and usually also additional voltages for biassing and focussing purposes. These, and other accessory circuits already mentioned in Chapter I, are nowadays housed along with the tube in a suitable case to form a self-contained and portable unit. The various circuits are described in some detail in the present chapter.

**D.C. Power Units.** The main purpose of the power supply is to provide the H.T. voltage for the anode. When the tube has a hot cathode, low-voltage heating current is also supplied ; and when there is a cathode shield, electron lens focussing or both, the different voltages for the electrodes are likewise obtained from the power unit. For metal tube models, a relatively large H.V. oil-immersed transformer is needed and a rectifier of either the valve or metal type. A circuit for each of these is given in Figs. 17 and 18 respectively.

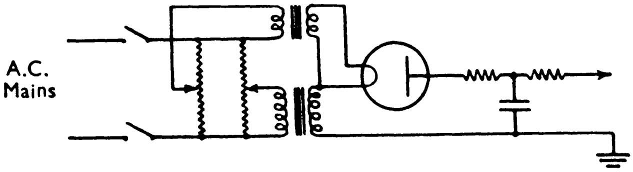


FIG. 22.—80 kV H.T. unit with valve rectifier.

Both are designed for maximum ratings of 80 kV (peak) and 2 mA, the sizes of the components being proportioned on this basis ; but values for other ratings can be easily derived. The first, viz., Fig. 22, employs a diode valve,* providing half-wave rectification, which is smoothed by the reservoir condenser and resistance. A filament transformer is needed for the valve, developing 15 volts ; but the secondary circuit must be insulated for the full 60 kV (R.M.S.) to the core and primary winding. The main transformer needs only a single 60 kV bushing, the other end of the secondary winding being at earth potential.

When metal rectifiers are used, the voltage doubler circuit, as shown in Fig. 23, is preferable, since it gives full-wave rectification, as well as

* For characteristics of thermionic valves, see Appendix A.

requiring a transformer secondary voltage of only 30 kV. The transformer secondary must, however, be provided with two bushings, one for 30 kV and the other for 60 kV. This is the more economical and robust scheme, and the one preferred by the author.

For glass tube oscillographs, simple power units almost exactly like those of a wireless set are fitted if a mains supply is available, or L.T. and H.T. batteries where these are appropriate. A typical diagram for the former is given in Fig. 24. The very small current demand renders the design an easy matter, as resistance-capacity smoothing is quite satisfactory. Connections between the potential divider and the various electrodes are exemplified later in Fig. 45.

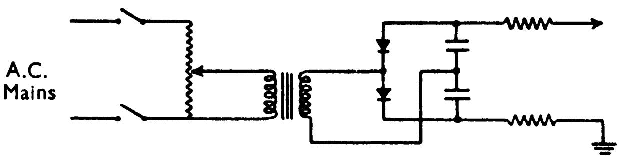


FIG. 23.—80 kV H.T. unit with metal rectifier.

**Time Bases.** There are a number of simple methods whereby the spot can be traversed at a rate varying in some way with time. For example, the deflectors may be energised from the 50-cycle supply mains, and either the whole wave may be used, or a selected portion may be magnified and so made to give a nearly linear travel. The usual method, however, is to make use of the rising or falling voltage due to the charge or discharge of a capacity. If, for example, the deflector terminals are connected to a condenser that is being charged or discharged through a resistance, the time scale will be exponential, which suits such records as lightning and other high-frequency surges, where the length of tail requires to be compressed. If a strictly linear time base is essential, then the condenser is discharged through a saturated diode or a pentode valve, either of which possesses a flat anode current-voltage characteristic and hence regulates the current at a nearly constant value.

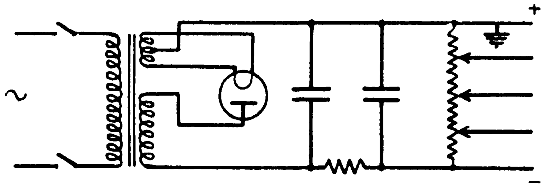


FIG. 24.—H.T. supply unit for glass tube oscillograph.

Time bases are divided into two classes, depending upon the purpose for which they are to be employed. The most common requirement is for recording recurrent or cyclic phenomena, such as the output of an alternator, transformer, or rectifier ; and for these a repeating time base, which is able to superpose a continuous succession of records upon the screen and thus produce a stationary image, is of considerable advantage. For non-recurrent transients, such as lightning or switching surges, a single-sweep base is appropriate. The two types may be compared with trembler and single-stroke electric bells respectively.

In each case, a triggering device is required, for the purpose of determining automatically the correct instant for starting the sweep ; except of course when a fluctuating voltage, such as that derived from the mains or an oscillator, is employed. Some kind of valve action is called for, capable of initiating the discharge of a condenser when a voltage exceeding a predetermined value is received. A discharge gap, either in the air or in a residual gas, is an obvious solution ; while the thermionic valve, either hard or gas-filled, may be used. The method of application will vary somewhat in the two cases.

The characteristics of the various alternatives are as follows :—

(1) Spark gap. A spark in air forms a simple and reliable " trigger " for high voltages exceeding about 2 kV. Below that point it is liable to introduce an appreciable and erratic time-lag. It fulfils the requirements for recording lightning and other high-voltage surges for which a single-sweep is appropriate.

(2) Gas-filled discharge tubes. When the gap is enclosed in a residual inert gas, such as nitrogen, argon, neon, krypton or xenon, consistent results are given down to a fairly low voltage, which is about 400, 300, and 200 in the cases of the first three gases respectively. All soft tubes, however, suffer from a slight sluggishness due to the relatively slow movement of the gas ions, causing a delay of from about 1 to 10 micro-seconds ; and there are cases where this would be objectionable. The most serious defect of gas discharge tubes is, however, that the range of voltage between striking and cut-off is relatively low, and the consequent movement of the spot is apt to be inconveniently small unless an amplifying valve is added.

(3) Gas-filled triode. The gas-filled valve, or " relay," enables reliable operation to be given at practically any voltage, its " firing " point being determined by the grid bias. The valve is connected across the condenser in very much the same way as the neon tube, with its grid voltage adjusted by means of a potentiometer. When the anode potential has risen to the point (determined by the setting of the grid voltage) at which anode current begins to flow, the impedance of the tube suddenly falls almost to zero, discharging the condenser. Upon the anode voltage collapsing in this way, the tube again becomes insulating, and

the condenser recharges. Advantages of the method are the adjustment of the " firing " point and the much greater range between discharge and cut-off points ; but the gas filling introduces the same short delay as with the previous type.

(4) Hard valves. The best known method involving hard valves is the cross-connected pair sometimes called the " multi-vibrator," which is embodied in Fig. 25. Each valve has a resistance connected between its anode and the H.T. supply, and the anode is also connected to the grid of the other valve. The effect is that an anode current in one valve causes a voltage drop in its resistance, which is communicated to the grid of the other. The latter is thus biassed more negatively than before, and its anode current is reduced ; and since this effect is cumulative, the starting of an anode flow through one valve immediately causes the current in the other to cease, and that in the first to rise instantly to a maximum. The device thus possesses a very definite " snap " action, analogous to that brought about mechanically in a tumbler switch.

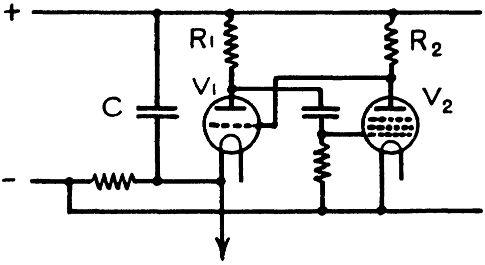


FIG. 25.—Puckle hard valve time-base.

Under quiescent conditions, a small anode current is kept flowing in one of the valves, by connecting its grid to the filament through a resistance. The voltage impulse is applied to this grid, raising its voltage in turn and bringing about the instantaneous operation of the other valve. Both the " Puckle Switch " (Fig. 25) and the " Kipp Relay " (Fig. 30) make use of the above scheme.

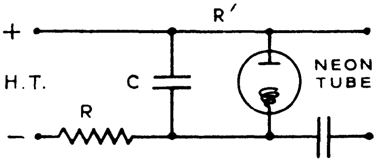


FIG. 26.—Simple time base circuit.

**Repeating Time Bases.** A simple circuit whereby repeating sweeps are generated is shown in Fig. 26. A condenser C is charged through the resistance R until its voltage reaches the striking voltage of the neon tube. The condenser will then discharge suddenly until the cut-off voltage of the tube is reached, and thus a " saw tooth " wave, as illustrated in Fig. 27, is obtained which is suitable for recurrent phenomena. The deflecting plates are connected to the right-hand terminals, and the gradually rising voltage will traverse the spot rapidly at first, while the voltage of the condenser is relatively low, but more slowly as it becomes charged, the rate of movement thus varying exponentially. The record is made during this relatively gradual sweep, and the spot " flies back," nearly or quite invisibly, to the starting point, along the sudden descent of the saw tooth.

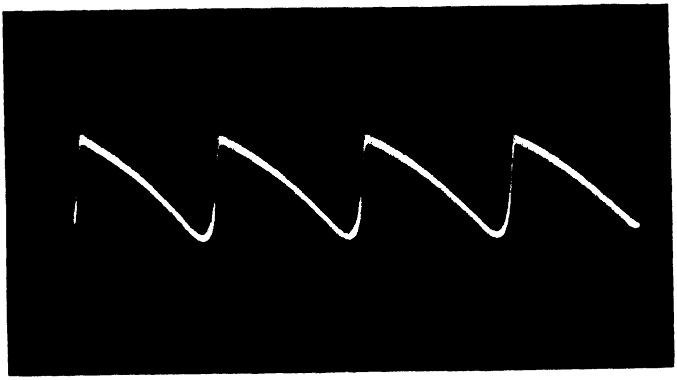


FIG. 27.—Saw-tooth wave generated by neon tube circuit. N.B.—The flyback is just visible in this oscillogram.

Modifications of this circuit are shown in Fig. 28. In the first scheme, the resistance R is replaced by a diode or pentode for giving a steadily rising voltage ; a triode being generally used for the former, with its unwanted grid connected to the anode. Regulation of the rate of charge is effected by varying the filament current of the diode, or the screen-grid voltage of the pentode. The gas-filled triode (or gas-filled " relay ") has a similar characteristic to the neon tube, in that the gas-filling ionises and hence becomes conductive when the condenser voltage has risen to a certain critical value, which can be controlled by varying the grid bias, and which may reach or even exceed 1 kV. Both of these features offer considerable advantages over the neon tube, and the gas-filled valve, or later type, has hence been substituted in practically all modern oscillograph sets.

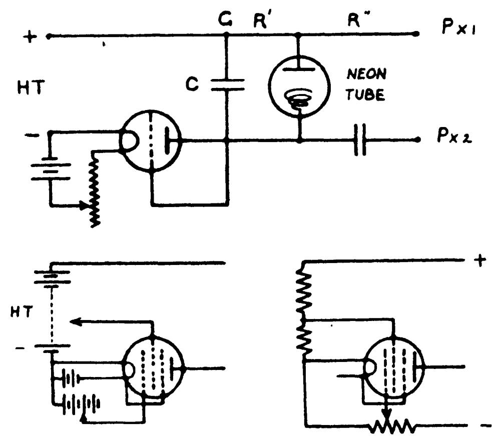


FIG. 28.—Linear time base, using (above) a saturated diode or (below) a pentode, shown for either battery (left) or mains (right) operation.

The Puckle switch, shown in Fig. 25, enables the same function to be carried out with a greatly extended frequency range, reaching well over $10^6$ c/s. ; and with a much smaller tendency to drift when mains fluctuations occur than is possible with a gas-discharge tube. As C charges, valve $V_1$ at first passes no anode current, as it is biassed beyond the cut-off point by the voltage drop in the resistance $R_2$ in the anode circuit of the second valve $V_2$, until the voltage across $V_1$ reaches a critical value at which anode current begins to flow. This causes a voltage drop in the resistance $R_1$, which is communicated to the grid of $V_2$ through the condenser, reducing the current $R_2$. The grid voltage of $V_1$ thereupon rises, the anode current then increases, and the action is cumulative. When the discharge is complete, the current in $R_1$ drops, the reverse action takes place, and the circuit returns to its starting point for the next saw tooth cycle.

As regards the scope of the above types, the gas-filled triode is commonly used for purposes not requiring a sweep frequently exceeding about 50 kc/s. Above this the hard valve possesses an increasing advantage, and is compulsory for the highest values of frequency.

**Synchronising Arrangement.** For the visual examination of a recurrent wave it is very advisable, and for photographic recording it is necessary, that the image be held stationary upon the screen. Without some addition to the above arrangement, this will involve a very exact adjustment of the time base frequency (effected by varying the filament current of the diode, or the grid voltage if a pentode is employed), to obtain synchronism with that of the wave ; and what is often more difficult, the maintaining of both frequencies absolutely constant while the examination is taking place.

It is, however, possible to control the striking of the discharge tube in such a way that the time base synchronises automatically with the " work " as soon as the two frequencies approximately match, and the usual incidental variations then produce no disturbing effect. This is accomplished by injecting a small portion of the " work " voltage into the tube circuit. In Fig. 26, or 28, a resistance is inserted at R′, which is made fairly high, but not sufficiently so to retard the fly-back appreciably. The Px connection is now taken to G, and a lead from the Py (or work) connection to the upper terminal of the discharge tube through another resistance and a blocking condenser. By this simple means a great gain in ease of manipulation is secured.

A refinement of this scheme consists of introducing a triode valve, the connection from the " work " voltage going to its grid. Not only is the work circuit thus separated from the time base, but the added amplification enables a much weaker signal to effect synchronisation. A similar method is used with the Puckle switch, by injecting a small proportion of the work voltage into one of the grids of the second valve $V_2$.

**Suppression of Flyback.** The flyback, forming as it does the steep descending portion of the saw-tooth wave, is executed at a much greater speed than the forward travel, and is hence much less visible than the working record. Although there is seldom much chance of its presence causing confusion, its complete suppression is frequently worth while, and can be brought about quite definitely by suitably varying the shield (or " grid ") voltage for the return trace. Making the shield more negative reduces the flow of electrons, and this is accomplished by means of a connection from the anode of the discharge tube through a condenser to the shield itself. The oscillogram in Fig. 27 (see p. 36), where the flyback is not suppressed, should be compared with those on p. 100, which were taken with an oscillograph having the provision just described.

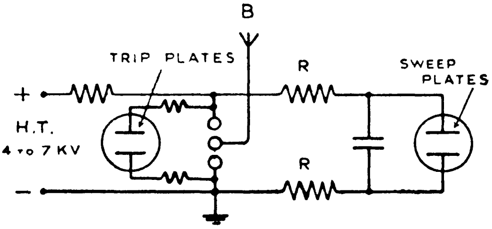


FIG. 29.—Single sweep time base for high voltage surges.

**Single Sweep Time Bases.** When the sweep is not required to repeat itself automatically, the circuit is a slightly simpler one, and can be derived when necessary by a slight switching modification of the repeating base.

A typical base suitable for recording lightning transients by means of a metal-tube oscillograph, and requiring a H.T. supply of from 4 to 7 kV, is shown in Fig. 29. The initiating impulse is picked up by the short aerial B, which is placed near the surge generator and leads to the middle of the three spheres forming a double spark-gap. The lower half of the gap immediately discharges to earth, and the upper half, being left to take the full voltage, promptly follows suit. This short-circuits the voltage not only of the trip plates shown on the left, but also of the sweep plates through the balanced resistance RR on the right ; and the condenser shown in parallel with the latter then discharges, providing the single exponential sweep.

The Puckle switch (Fig. 25) is converted to a single sweep base by means of a simple switch short-circuiting the resistance between grid and cathode of the valve $V_2$. With this resistance cut out, the voltage drop across the resistance $R_1$ can no longer be injected into the grid of $V_2$, and the sweep therefore does not repeat.

The Kipp relay circuit is shown in Fig. 30. Since it must be actuated by waves of either polarity, and the thermionic valve, in contrast to the spark-gap, is polarised, a third valve, $V_3$, is added, which deals with the positive impulses, leaving those of negative polarity to $V_2$. The effect of the cross-connection of the two main valves has already been described.

Under quiescent conditions the grid of $V_2$ is kept at filament potential by the grid resistance, and a steady anode current consequently passes through $V_2$, rendering $V_1$ non-conductive. The arrival of a negative impulse at the grid of $V_2$ stops its anode current and conditions instantly reverse, $V_1$ now conducting and initiating the sweep ; while, although $V_3$ also receives the impulse, it is so biassed as to be unaffected by one of negative polarity.*

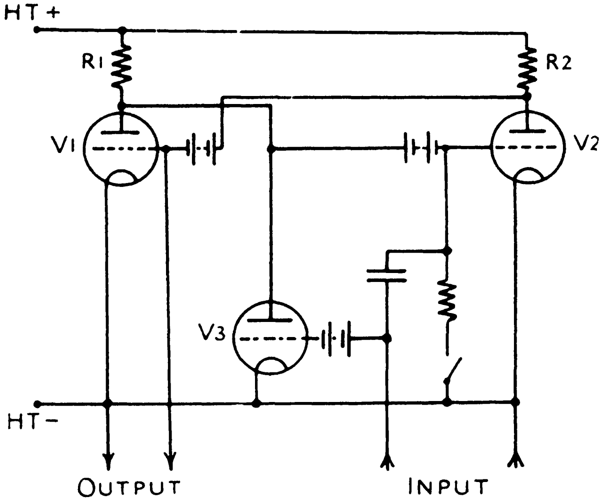


FIG. 30.—Kipp relay.

A positive surge, however, which cannot alter the condition of $V_2$, causes $V_3$ to pass an anode current through $R_1$, thus reversing conditions as before. Hence surges of either polarity render $V_1$ instantaneously conductive.

**Independent Bases.** When the horizontal transverse is proportional to some other quantity than time, the circuit becomes much more simple. The usual procedure is to derive the fluctuating voltage from the 50-cycle mains, which would form the independent variable and be connected to the horizontal deflectors. The dependent variable,

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* For anticipatory triggering, see note on p. 127.

*i.e.*, the quantity varying as the result of the change of voltage, would then be impressed upon the vertical deflectors ; and the result would be a complete graph connecting the two variables and repeated *n* times per second, where *n* is the supply frequency.

There are, however, a few slight elaborations that may be necessary or desirable, and four of these deserve mention. First, it is sometimes advantageous to rotate the phase of the traverse by a given angle. This is accomplished by connecting the leads to a capacity and resistance in series, and tapping the plates across the capacity. The values of the two components are proportioned to give reactances at the frequency employed that will produce the phase angle required on the usual basis of $\tan \phi = X/R$. For example, for a shift of 90°, where $\tan \phi = O$, R would require to be infinitely large, and in practice is made at least ten times X, or $10/(2\pi fC)$. Similarly for a shift of 45°, $X = R$. An example of a 90° phase shift occurs in Fig. 67.

A similar requirement occurs when a quantity has to be obtained from a circuit which gives the rate of change of the quantity. As the latter is the differential of the quantity required, it must be integrated before being applied to the deflector plates. An example is found in connection with the taking of the B/H curve of a steel sample, where the flux density B is obtained from the induced voltage in a coil embracing the iron, as described later on p. 151. Again the plates are connected to a capacity which is in series with a high resistance, the rate of change being applied to the combination. Now the voltage across the condenser $= q/C$, where $q =$ charge in the condenser. But for a varying current, q is the integrated current with time. When the capacity reactance is negligible in comparison with the resistance, the voltage may be assumed to vary as the current, and hence q is proportional to the integrated voltage. That is, the voltage across the capacity is the integral of that across the capacity and resistance in series.

The converse operation of differentiation is occasionally required, *e.g.*, in connection with the brilliancy control unit described on p. 45, where the bias potential is made to vary as the rate of change of the deflecting voltage. A corresponding method is employed, by connecting a resistance and capacity in series across the voltage to be differentiated, but the connections and adjustments are the converse of those used for integration. In the present case the resistance R must be negligible compared with $1/(2\pi fC)$, and the output is taken from the resistance terminals. The principle depends upon the current through the combination being the rate of change of charge ; *i.e.*, $I = dq/dt$, and consequently the voltage across $R = IR = R.dq/dt$. But $q = Cv$, where v is the voltage across the condenser, which may be taken as the total voltage V, as R is assumed to be negligible. Thus output voltage = RC.dV/dt ; *i.e.*, it is proportional to the differential of the applied voltage.

For both integration and differentiation, a resistance and an inductance could be substituted for a capacity and a resistance ; but the latter combination is usually the more convenient.

Finally, a more open and therefore more readable trace is desirable when the oscillogram includes a number of evenly spaced peaks. Now the traverse due to a sine wave crosses and recrosses the screen from left to right and back from right to left alternately, the " going " and " return " records being superposed on each other and often producing a confused effect. These two portions can be separated by converting the straight line motion into a circular or elliptical course ; which can quite easily be accomplished by adding a quadrature component, formed as in the first modification, to the traverse. The circuit for producing such a base is given in Fig. 31, and the resulting oscillogram is exemplified in Fig. 32.

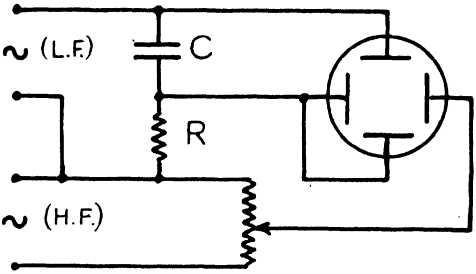

Fig. 31.—" Phase-splitting " circuit for producing elliptical or circular figure.

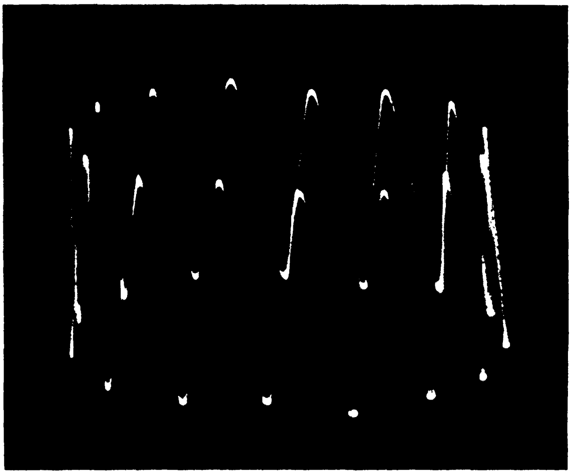

Fig. 32.—Example of elliptical figure produced by circuit in Fig. 31.

**Voltage Dividers, or Attenuators.** A voltage divider is simply a resistance or capacity which is " tapped," or used after the manner of a potentiometer ; that is, the voltage is applied across the whole impedance and the desired fraction drawn off from a section, usually situated at the earthed end.

For tests carried out in the field, for example on overhead transmission lines, capacity type dividers are employed. The simplest arrangement consists of a string of link insulators suspended from line to earth, with the instrument connection taken across the last unit. In this case the links function as condensers ; and it is of interest to note that the capacity of a single cap-and-pin insulator link is about 30 $\mu\mu$F. Other types of condenser would be preferable for outdoor tests that must be carried out in all weathers.

Resistance dividers are more usually employed for indoor tests, and may be either liquid or wire-wound. The latter are the more permanent, and may consist of resistance wire wound on flat mica strip and oil-immersed. The former may be composed of tap-water contained in glass or other insulating tubes. In both cases the most convenient procedure is to make the lower section adjustable and treat the portion above the tapping as fixed.

In connection with voltage dividers generally, it must be borne in mind that inductance is present to some extent, and may interfere with the voltage ratio if its value is allowed to become appreciable. At public supply frequencies there is no likelihood of trouble ; but with high frequencies, such, for example, as those that may be reached in a lightning surge, the inductive reactance even of a straight conductor may not be negligible.

**Amplifiers.** The sensitivity of the usual glass tube oscillograph is about 25 volts per inch. For the numerous cases where voltages are too low to give a workable direct deflection, amplification is employed as in wireless practice, but with two main qualifications. First, it is now even more necessary to avoid distortion over the working range, since inaccuracy would be the direct result. Secondly a certain amount of D.C. is often present in the wave, which it may be desired to record. At least the second of these conditions rules out transformer coupling.

The first condition requires that the gain at any adjustment shall be constant over the usual working range of frequency, and reasonably constant at extreme values, either high or low. Further, since one of the principal advantages of the cathode oscillograph is a very low drain of power from the circuit under test, this quality must be possessed by the amplifiers also. The requirement is met by the use of a high impedance first valve, of at least half a megohm for general work. No appreciable capacity must be introduced at the input terminals of the amplifier.

As regards the reception of direct currents or D.C. components, it is frequently an advantage that these shall be stopped, as, for example, when ripples in the voltage of a rectifier or D.C. generator are being examined. But this is not always the case with transient D.C. components, which can in any case get through a coupling condenser, provided its capacity is sufficient to accept the D.C. charge without serious rise of potential.

For other cases, where a large or continuous direct current is to be recorded, a special arrangement may be necessary, depending on the degree of amplification. When the incoming signal is strong enough to be taken directly to the deflectors, there is no difficulty. The same applies when there is only a single stage of amplification, and the signal is connected directly to the grid of the amplifying valve. But when more than one stage is used, inter-stage coupling is necessary, and resistance coupling must be used without the capacity. Now the function of the latter is to isolate successive stages from one another, and so avoid short-circuiting the gain voltage. Since isolation is not now possible, a compensating voltage must be added to balance the gain, and this is usually inserted at the gap between H.T.1 – and H.T.2 – in Fig. 33. In some cases a battery or potentiometer might serve, but the most stable method is by means of an additional valve, as shown at $V_A$.*

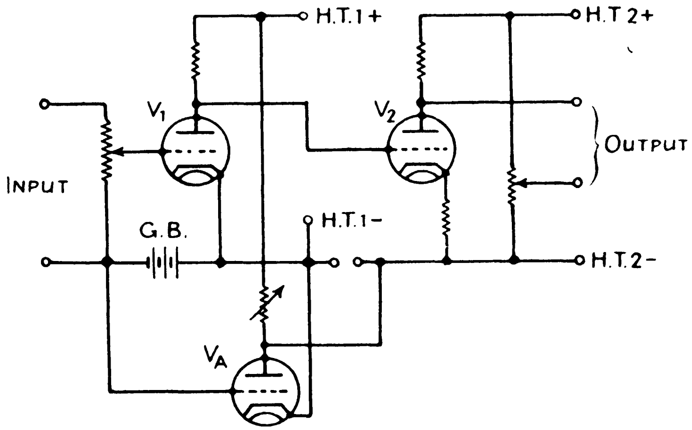

Fig. 33.—Arrangement of amplifier for D.C. voltages.

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* See Millman and Moskowitz, "Tracing Tube Characteristics on a Cathode Ray Oscillograph," *Electronics*, March, 1941, p. 36.

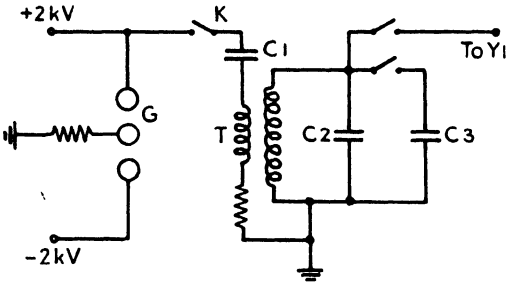

FIG. 34.—Timing wave circuit (Standard Telephones and Cables Ltd.).

In general, amplification is not required to the same extent for both sets of plates. A time base does not usually need any, and accordingly small oscillograph "sets" often possess only the one amplifier. A good instrument for general testing, where both X and Y deflections may be used for quantities other than time, might have a two-stage amplifier for one pair of plates and one with a single stage for the other. The necessary controls are provided for using one or two stages, and for varying the gain as required.

As regards accuracy, even the smallest present day oscillograph should possess a flat response characteristic over a range of 50 to 10,000 c/s, while recent larger models will operate evenly over a much greater range, such as 10 to 100,000 or even 2,000,000 c/s. Considerable improvements in amplifier design have been made during the past few years under the stimulus of television requirements, and the standard is still rising. An extension of the range to 5 Mc/s is to be expected in the near future.

**Time Marker.** A time scale is often required on an oscillogram, especially when the time base is non-linear, and may be inserted in two ways. First it may consist of a series of very short interruptions, variations in intensity or peaks in the main oscillogram. Of these, the first two would be obtained by variation of the grid (or modulator) voltage, by means of a series of evenly spaced breaks or pulses, *e.g.*, from a tuning fork. For the last, pulses from a similar source would be applied to the deflector circuit.

Secondly, it may be added to the record either before or after the main oscillogram has been taken, by connecting the vertical plates momentarily to an A.C. source, such as an oscillator, of known frequency. The simplest self-contained arrangement consists of a small transformer, the primary of which can be given an impulsive discharge, setting up a train of oscillations in the tuned secondary. An example, used in the S.T.C. Transient Recorder, is shown in Fig. 34.

A surge is applied to the spark-gap G, causing it to break down while the key K is depressed, connecting the upper sphere to the primary through the condenser $C_1$. The shock excitation so applied to the secondary causes it to oscillate at a frequency of 1 Mc/s when the tuning is due to $C_2$ alone, and 250 kc/s when $C_3$ is added in parallel with $C_2$. Damping is sufficiently low to enable a long series of waves to be recorded before the amplitude falls below the useful value.

**Automatic Brilliancy Control.** Various conditions require varying degrees of beam brightness. For example, if the spot is to remain stationary on the screen, the intensity must not exceed a certain limiting value, otherwise the fluorescent material, or even the glass itself, may be damaged. For this reason the beam is very often trapped, or modulated out of existence by modifying the grid bias, when it is not actually tracing a record.

But in many cases the brilliancy should preferably be varied during the actual taking of an oscillogram. A constant beam is satisfactory for curves that do not vary their inclination to any great extent, such as circles or sine-waves ; but for those possessing sharp peaks denoting a considerable increase in writing speed, the requirement is not so simple. If the intensity is correct for the slow-speed portions, the steep parts will be dim or even invisible ; as often happens in connection with lightning surges and other steep-fronted waves. If, on the other hand, the spot is made brilliant enough for the highest writing speeds, the slow-speed portions will be over-exposed, showing a thickened trace, surrounded by halation fog.

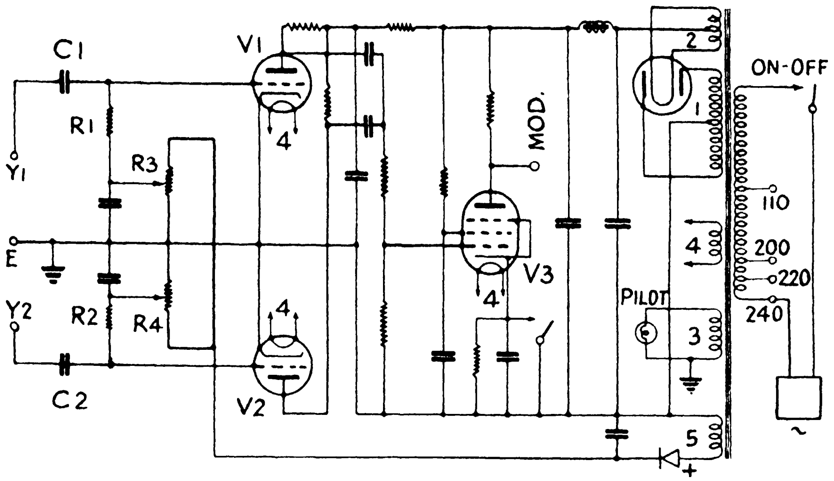

FIG. 35.—Automatic brilliancy control unit. (Cossor.)

A method for suitably varying the brilliancy was suggested by Professor Schonland, of South Africa, and developed by Messrs. Cossor, the resulting scheme being shown in Fig. 35. The basic requirement is that the brightness shall vary as the writing speed, *i.e.*, as the rate of change of deflection ; and since the deflection is proportional to the deflecting voltage, it follows that the brightness should vary as the differential coefficient of the voltage applied to the Y plates. In the scheme, the latter voltage is therefore differentiated, and the resultant is amplified and taken to the cathode shield (or grid) of the oscillograph tube.

Duplicate provisions have been made for dealing with both positive and negative surges. Differentiating circuits $C_1R_1$, $C_2R_2$ are interposed between the " vertical " deflecting terminals $Y_1$, $Y_2$, and the grids of the first amplifying values $V_1$, $V_2$; and the output from the anode of the pentode power-valve is led to the modulator (shield) terminal of the cathode tube. The potentiometer connections $R_3$, $R_4$ will be recognised as the grid bias supply to $V_1$ and $V_2$ ; while the D.C. power supply on the right follows standard practice.

When the above scheme is in use, the initial brilliancy of the tube must be adjusted at a value sufficient for slow speeds, up to that at which automatic regulation begins. At the upper end of the scale, the pentode output stage is designed to saturate when the maximum modulation voltage of the oscillograph tube (about 50 volts) has been reached, in order that the focus shall not suffer if exceptionally high writing speeds should occur.

**Multiple-trace Circuits.** There are three ways of securing more than one independent trace or record with the cathode oscillograph. First, two or more separate tubes may be used, as described later on p. 65. Secondly, a double-beam tube will provide two traces, and a more elaborate scheme of a somewhat similar kind has been used to give four. Thirdly, two or even more traces may be obtained on the screen of a standard single-trace tube by the use of a mechanical rotating commutator, or of one or more " electronic " switches.

The principle of the last type is the rapid switching of the deflectors from one deflecting circuit to another in such a way that two apparently continuous traces are produced, the transfer being accomplished so rapidly as to leave no visible impression. It is a tribute to the great flexibility of the electron tube that this apparently far-fetched scheme is effected with complete success.

Electronic switches are composed of several distinct stages. First, it is necessary to generate a " square " wave, *i.e.*, one that remains parallel with the axis for a certain time, moves with great rapidity to a corresponding position on the other side of the axis, and keeps on repeating this action at the desired frequency. Such a wave is generated by the " multi-vibrator " or " flip-flap " described on p. 35, and there are other ways of producing it. Then by applying the square wave to the suppressor grid circuits of a pair of pentodes, but in opposite directions, they can be made to connect the vertical deflectors to the two signals alternately.

The switching frequency can be chosen to fulfil either of two conditions. First, it may be quite independent of that of the sweep, and is then usually at a much higher value ; or secondly, it may correspond with the sweep frequency or a multiple thereof, so that alternate cycles are devoted to the two waves in turn. In the first scheme, the spot is continually crossing over from one wave to the other in the oscillogram, so that both records in any one traverse are only semi-continuous, and the space between them is crossed by the spot $2f_1/2f_2$ times per second, where $f_1$ and $f_2$ are the switching and sweep frequencies respectively. There will thus be a faint " curtain " of light between the two traces, though usually the switching speed of the vertical parts of the square wave is sufficient to render it inappreciable.

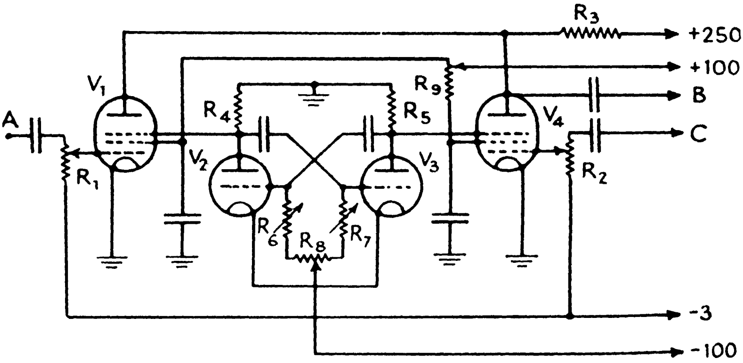

FIG. 36. Electric switch for independent frequency working.

A circuit for such a switch is specified by Strong * and is given in Fig. 36 herewith. In this, the two middle valves and their connections will be recognised as the multivibrator circuit, which is able to apply negative pulses of about 85 volts to the valves $V_1$ and $V_4$ in succession, suppressing their anode currents in turn. Thus the two inputs, connected to A and B respectively, are delivered alternately to the common output at C.

Although each individual impression is discontinuous, successive sweeps will cause the gaps to fall on different parts of the trace, and thus the trace appears continuous, unless the sweep frequency is near to a multiple of the switching frequency. In order to avoid the latter, it is only necessary to provide the grid resistors $R_6$ and $R_7$ with a slight and preferably ganged adjustment, which is able to make a small change

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* See " Two Forms of Electronic Switch," *Jour. Sci. Instruments*, 1940, Vol. 17, p. 275.

in the relaxation period. The tapping-point of the resistance $R_8$ joining $R_6$ and $R_7$ is also made adjustable, whereby the time constants can be unbalanced, causing one pulse to last longer than the other and the trace to appear correspondingly the brighter. This assists considerably in distinguishing the two waves from each other when their traces are entangled. Finally, the variable resistor $R_9$ enables the screen voltages of the pentodes $V_1$ and $V_4$ to be unbalanced. By this means the axes of the two waves are moved apart, as in the lower part of Fig. 37.

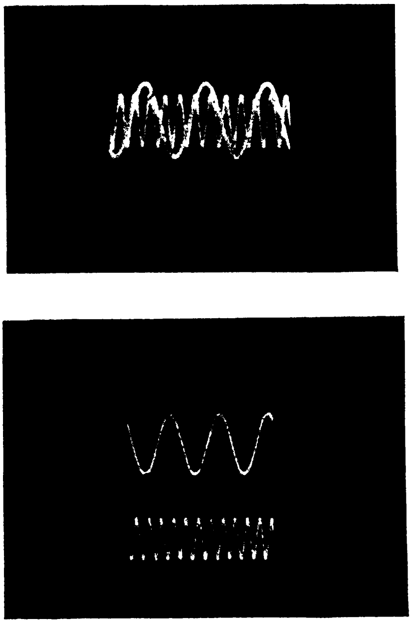

FIG. 37.—Double-wave recording by the Dumont electronic switch, showing effect of screen voltage adjustment.

Three records may be obtained by the use of two electronic switches, the output of one being connected to one of the inputs of the other ; and the principle is capable of further extension if desired.

An incidental advantage of the high-frequency electronic switch is that the coupling condensers of the amplifier do not in general have to accept a direct current for any appreciable time, even when one of the traces is wholly or largely D.C. It is therefore possible to record D.C. components accurately without the complications described on p. 43.

A modified scheme in which the multivibrator is triggered by the sweep circuit, and hence switches over alternate sweeps, is also described by Strong.* Four similar tetrodes (KTZ63) are used. This circuit exemplifies the second type of electronic switch, which possesses some small but definite advantages over the first. The traces are always continuous and the background free from stray light ; and interference between the two amplitudes is quite absent. The only possible drawback is an increased tendency to flicker at low sweep frequencies.

The oscillograms in Fig. 37 were obtained by means of the Dumont electronic switch, and illustrate the simultaneous recording of two frequencies, one much greater than the other. In this model, the switching speed may be varied between 6 and 2,000 operations per second ; and the switching frequency may be independent of all other frequencies, or locked to the frequency of either wave. It can therefore be used in both ways that have been described. The oscillograms in the figure were obtained by the second (locked) method. Incidentally, the square-wave generator may be used by itself to provide waves that are sufficiently square for general purposes at frequencies ranging from 60 to 400 c/s.

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* *Ibid.*

**Enclosures.** The cathode ray tube is very seldom used without some kind of enclosure. Mention has already been made of the necessity for magnetic screening to prevent interference by stray fields ; and this alone implies encasement by iron of good permeability when very sensitive results are required or when stray fluxes are liable to be set up by neighbouring plant. In addition, the glass tube models are portable, and need cases for carrying and protection purposes.

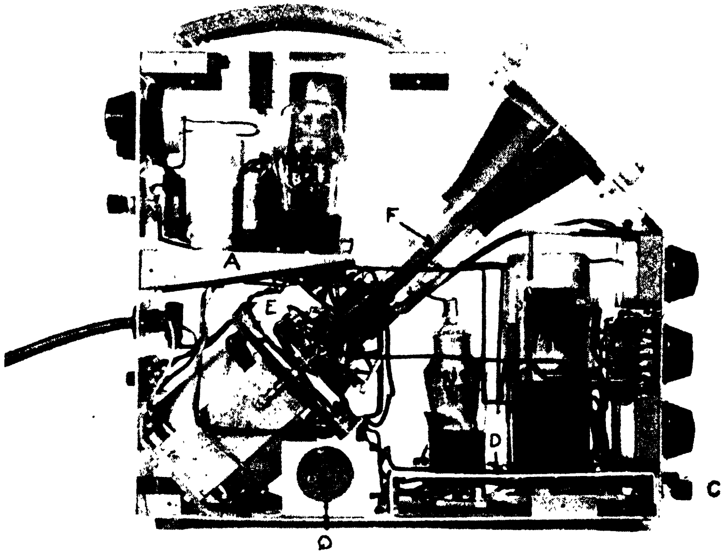

FIG. 38.—Arrangement of accessory circuits and main tube in aluminium case for small portable set described on p. 60.

To begin with the more difficult problem of the metal tube instrument, the two models shown in Figs. 4 and 52 (front) pursue opposite policies in this respect. The larger model is not itself enclosed, as access is required at many points for purposes of adjustment or operation ; while the parts are so robust that further protection than that afforded by the metal tube and drum-case is unnecessary. But the room in which it is housed in a typical installation is lined with mild steel sheets, ¼ in. thick. The somewhat smaller three-phase model, on the other hand, is contained in a steel enclosure, together with pumping equipment, and is therefore entirely self-contained and screened.

Glass tube oscillographs are housed, together with their amplifiers and time-bases, in cases which closely follow wireless-receiver practice. Aluminium containing cases are usual, providing electrostatic screening. It is not practicable to apply much magnetic screening to portable models, as the weight would be very seriously increased if this were done. Interference between the various magnetic circuits is minimised by careful disposition of the components, and screens can thus be restricted to a tube of high-permeability alloy round the most sensitive part of the cathode ray tube, and possibly a comparatively small barrier of the same material elsewhere. The arrangement of the accessory circuits, as well as of the main tube, is exemplified by the open view of the small portable set in Fig. 38.

## CHAPTER FOUR

# MODERN TYPES OF CATHODE RAY OSCILLOGRAPH

The components that have been described in the preceding chapters have been combined by various designers to form " sets " having different capabilities suitable for different classes of work. Some attention will be given in the present chapter to the effects produced by certain factors and parts in modifying the characteristics, utility and convenience of the whole apparatus ; and examples will then be considered, additional to those dealt with in Chapter II, of representative oscillographs that have been designed within recent years.

**Gas versus Electronic Focussing.** The general characteristics of the two competing methods of focussing have already been given in Chapter II, pp. 19–22 ; and their relative advantages and disadvantages will now be considered.

To begin with, gas-focussed tubes can be used at 300 volts as compared with a minimum of about 1,000 for the high-vacuum type, and will at this voltage give a brighter and more sharply focussed spot, which is more than three times as sensitive as its rival. Yet the present tendency is for the gas-focussed type to be superseded.

The chief defect from which the gas tube suffers is short life, owing to the rapid deterioration of the cathode. Focussing is brought about by the presence of positive ions in the electron stream, many of which move in the opposite direction to the electrons. These constitute a continual rain of relatively heavy projectiles bombarding the cathode, with the result that its useful life is limited to about 200 hours, as compared with 1,000 to 2,000 hours in the case of the hard tube.

Origin distortion is a defect peculiar to electrostatic deflection in gas-focussed tubes, and consists of a reduction of sensitivity when the deflecting voltage is within a few volts on either side of zero. Consequently an evenly rising or falling voltage which passes through the zero value is shown by a line with an inflection in it instead of a smooth one. The bending is due to the shielding effect of the positive ions on the electron stream, for they have to be drawn into the plate by the electrostatic action of the voltage before the beam itself can be influenced. The effort required is not negligible for potentials less than about ± 8 volts, and reduced deflections over this range are the result.

There are two methods of obviating the trouble. The simplest is to shift the figure away from the zero line by means of the positioning controls ; but a complete cure is indicated in Fig. 12. Here one of each pair of deflecting plates is split, and separate leads are brought out to enable a potential somewhat exceeding the above value to be connected across the two half-plates in each case ; the requirement being that at least 8 volts nett is available when the spot is deflected to the limit of its useful range. This voltage deals effectively with the ions, and the deflection of the beam is not impaired by them.

More important is the partial or complete failure of gas-focussing at writing speeds above about 6 miles (10 km.) per second, owing to the ions, which are relatively slow moving, being left behind by the beam and thus ceasing to attract the electrons. The maximum frequency for which a gas-filled tube can be satisfactorily used is therefore restricted to 750 kc/s, as compared with over 500 Mc/s in the case of high-vacuum tubes.

Great improvements have been made in the high vacuum tube during the past few years, and the net result of all these factors is that this type can successfully fulfil any function previously carried out by the gas-focussed tube, and the latter is obsolete as a general purpose instrument. Its advantages are, however, still sufficient to secure its use in sets designed for a specific purpose, such as cardiography, where it can confer a higher degree of sensitivity and portability than the high vacuum type.

**Effect of Voltage.** There is wide variation in the voltage applied between cathode and anode in the case of the various forms of oscillograph. This is called the " anode " or " accelerating " voltage, as its direct effect is to accelerate the flow of electrons ; and should be distinguished from the deflecting voltages applied to the plates or coils. The general rule is that the higher the accelerating voltage, the more intense is the spot ; but tubes fall into three groups as regards their requirements in this respect. It is the great advantage of the hot cathode that it liberates the electron stream so readily as to enable low voltages to procure a satisfactory record. When gas-focussing is employed, a voltage as low as 300, or even less, will produce a brilliant spot.

High vacuum glass tubes employ a minimum voltage of about 1,000, which may rise to 3,000 or 5,000 volts for special purposes, such as the use of screens of extra large diameter or giving a long afterglow, the production of an unusually bright spot, or the recording of very high writing speeds.

Cold cathode tubes require extra high voltages, especially those of considerable length ; a common voltage for the 6 ft. continuously evacuated tubes being 40 to 60 kV. There is a possibility that the hot cathode may find an extended use in future in order to avoid such high potentials.

High voltage brings with it the drawback of decreased sensitivity ; for the deflecting voltage must increase with accelerating potential in order to produce the same deflection. Hence the voltage applied to a given tube is usually kept down to the lowest value that will give an adequate trace. There is, however, a further aspect that should be borne in mind, namely that the highly sensitive tube is readily affected by stray fields ; and the most satisfactory voltage is the compromise which best meets all the existing conditions.

Out of so wide a range, present-day practice is tending towards the following unofficial standards :

| | |
|---|---|
| Gas-focussed tubes . . . . . . | 300 volts |
| High vacuum tubes, with Willemite or blue screens . . . . . . . . | 1,100 ,, |
| Do., with red long-afterglow screens . . | 3,000 ,, |
| Do., for single-sweep transients . . . | 5,000 ,, |
| Metal tubes, with cold cathodes, 4 ft. long . | 15,000 ,, |
| Do., 6½ ft. long . . . . . . . | 50,000 ,, |

It is important, for the sake of the life of the tube, as well as the sensitivity, that the anode voltage should not be higher than is necessitated by actual conditions ; and it is usually brilliance of the trace that forms the deciding factor. Now the brightness of the image may be taken as varying with the anode voltage and inversely as the writing speed. Such waves as the characteristic curves of alternators or transformers do not involve any considerable change in speed, and a relatively low voltage will suffice for them ; but lightning or restriking transients have steep fronts in which the trace may become invisible if the beam is not an intense one. For this reason the " Transient

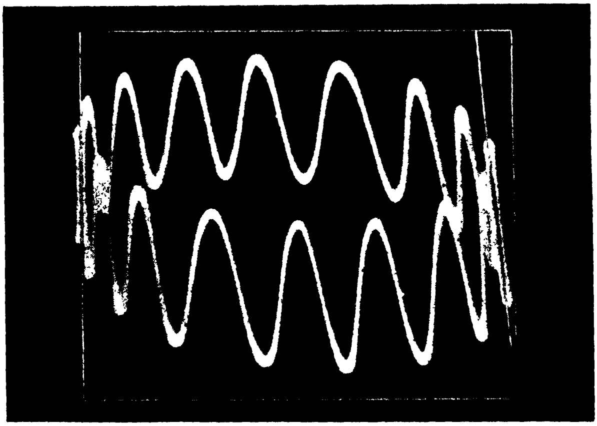

FIG. 39.—Example of trapezium distortion. The construction lines show the amount of the error.

Recorder," described on p. 42, has an accelerating voltage of 5 kV, and the metal tube shown in Fig. 52 one of 15 kV.

**Trapezium Distortion.** It follows from what has just been said that the accelerating voltage must remain at a constant value if the sensitivity is to be constant. This condition is not fulfilled if the first pair of deflecting plates is able to increase the voltage applied to the beam ; for then the deflections due to the second pair of plates will vary. If, for example, one of the first pair be maintained at constant voltage, and a rising voltage be applied to the other in order to traverse the beam across the screen, then the acceleration of the electron stream is increased as the beam moves across. In consequence, the effect of the second deflectors decreases during the same period, and a figure that should be rectangular is recorded as a trapezoid. An example is shown in Fig. 39.

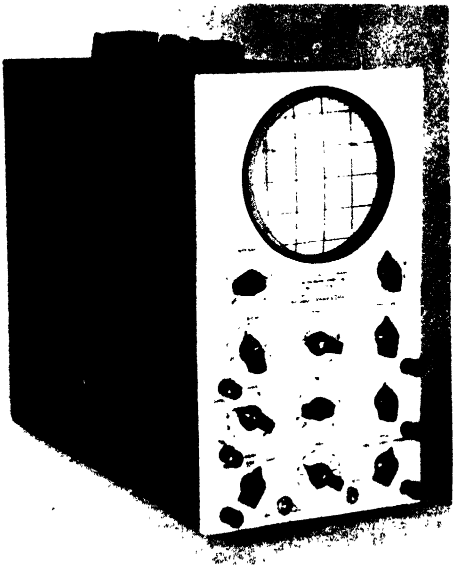

FIG. 40.—Dumont oscillograph.

The usual remedy is to maintain the average voltage at the first plates constant by means of balanced or " push-pull " deflection. To achieve this, separate leads must be brought out from all four plates, and the time-base (or other deflecting means) suitably modified. An example of a balanced deflection circuit is given in Fig. 42, later in the chapter.

Incidentally, balanced deflection also corrects a less noticeable effect in the shape of some loss of focus in the outlying parts of the figure, experienced when the deflecting voltage is asymmetrical.

A simpler corrective to both effects is illustrated in Fig. 10, where a screen connected to the final anode is interposed between the two sets of plates.

**Controls.** One of the great advantages of the cathode oscillograph is the large number of respects in which it may be controlled. This feature necessitates a correspondingly large number of control knobs, and some care is necessary in locating them to secure the desired simplicity and convenience of operation. The set shown in Fig. 40 possesses on its front panel eleven such knobs and two switches, and may be regarded as typical. More are needed for a double-beam tube, as in Fig. 43, but room is conserved here by the use of two knobs in "tandem" for six of the control points, the knob next the panel in each case being of larger diameter than that in front of it.

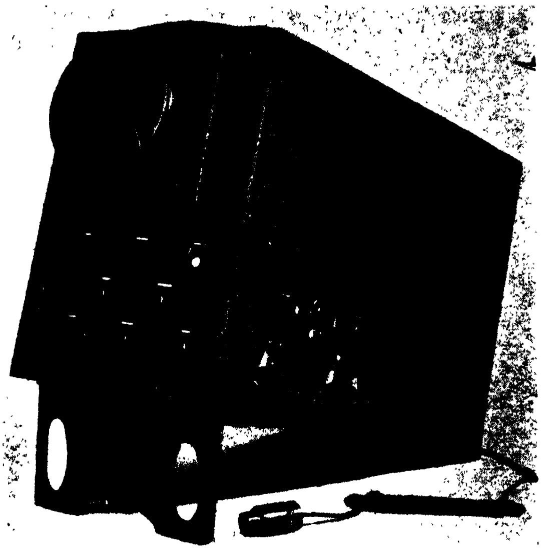

FIG. 41.—Cossor high vacuum oscillograph.

The knobs should be located according to a rational scheme, those that are usually associated being mounted close together. For example, the arrangement in Fig. 40 has the "vertical" controls on the left-hand side, and the "horizontal" in corresponding positions on the right. Controls for the tube (viz., intensity and focus) are placed in the top row, while those for the sweep circuits are on the vertical centre line. To simplify matters still further, the knobs that are used most frequently are coloured red, the remainder being black. It is also advantageous that the most used connections, such as the inputs for both sets of amplifiers, the sweep and the grid circuits, shall be in front. Other connections and switches may be located on a side or rear panel.

**Typical Examples.** Two examples of cathode oscillographs have already been described in Chapter II in order to illustrate the functions and arrangement of the various components. These were the Cossor glass tube and the Cambridge high-voltage metal tube. The gas-focussed pattern was dealt with in considerable detail, and some reference was made to the high-vacuum type, with single and double beams. Further consideration will now be given to the latter type.

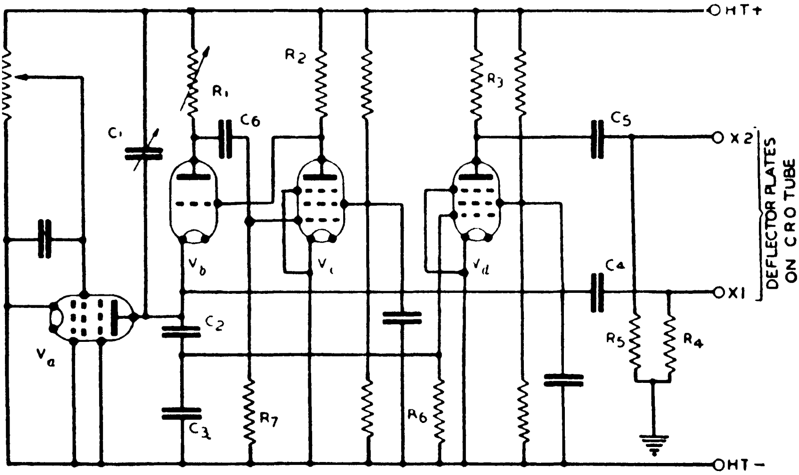

FIG. 42.—Basic circuit of oscillograph in Fig. 32.

**High Vacuum Oscillographs.** A few details have been given regarding the electron-lens focussing of the high-vacuum tube, and these will be supplemented by a description of various representative instruments.

COSSOR SET. The external appearance of the Cossor high-vacuum oscillograph is seen in Fig. 41. As is usual, a metal case houses the tube and accessory circuits, including the H.T. power supply, time base, amplifier, and calibrating circuit. Visibility of trace and convenience are enhanced by the cylindrical hood round the screen, and by the tilting foot. Protection is afforded to the user against high voltage by a device which prevents the case being opened without disconnecting the mains. The control knobs are on the front panel below the screen, while a key panel is situated on one side whereby the various connections can be made for the deflector plates, time base, amplifier and calibration. All four deflector plates of the tube are brought out separately, enabling trapezium distortion to be avoided.

The basic circuit is shown in Fig. 42, and incorporates four thermionic valves. That on the left, $V_a$, is a pentode working on the flat part of its characteristic and thus rendering the time-base linear. The next two, $V_b$ and $V_c$, constitute the Puckle discharge arrangement for the time-base condenser, which has been described in Chapter III. It is capable of developing frequencies up to 300 kc/s.

Finally, $V_d$ is a pentode of the same type as $V_a$ and $V_c$, and can serve two purposes. In the figure its grid is supplied from a capacity divider formed by $C_2$ and $C_3$, which are connected across the time-base condenser $C_1$ ; and its anode reproduces the same voltage changes as are developed across $C_1$, but with reverse polarity. The deflecting voltage of the X plates is therefore balanced, *i.e.*, in push-pull ; and trapezium distortion is consequently avoided. Secondly, a simple scheme is incorporated for reconnecting $V_d$ as an amplifying valve when this is required. Calibration is effected by means of a special winding on the mains transformer.

DUMONT SET. The Dumont oscillograph shown in Fig. 40 is a typical American general purpose model designed to meet the requirements of the average laboratory. It embodies a tube with a screen diameter of 5 in., working at an accelerating voltage of 1,100. A very convenient and full set of controls are mounted on the front panel, which is of chromium-plated brass, the remainder of the case being of steel ; while a terminal block is located on the rear panel.

Amplifiers are provided for both horizontal and vertical plates, these being single-stage for the former with a gain of 50 times, and single or double-stage at will for the latter with gains of 70 or 450 times. The tube has a deflectional sensitivity, when operated direct, of 20 volts (R.M.S.) per inch, and maximum sensitivities when the amplifiers are in use of 0·046 and 0·40 volts per inch for the vertical and horizontal plates respectively. Frequencies of from 15 to 30,000 c/s are given by the time-base, which is triggered by a gas-filled relay and is nearly linear over that range. The sweep output may be amplified to obtain much higher frequencies. Very positive synchronising is effected by a control knob. All the controls are calibrated, rendering it an easy matter to reproduce any setting. Control knobs in common use are distinguished by being coloured red. The total weight, viz., 31 lb., is low for so complete an instrument ; this weight being important as it is just about the highest that can be comfortably carried in the hand for any distance by an average operator.

DOUBLE-BEAM SET. The internal arrangement of the deflectors for a Cossor double-beam tube has already been shown in Fig. 9, and the whole instrument is illustrated in Fig. 43. Two separate beams are formed by the middle electrode bisecting the space between the outer plates, and they are both acted upon by the same X deflector plates. Hence they are alike in intensity and are cross-traversed at exactly the same rate ; but since the Y deflectors act in opposite directions, they are 180° out of phase in space. This arrangement enables comparisons between similar quantities to be effected with an exactness that is not otherwise possible.

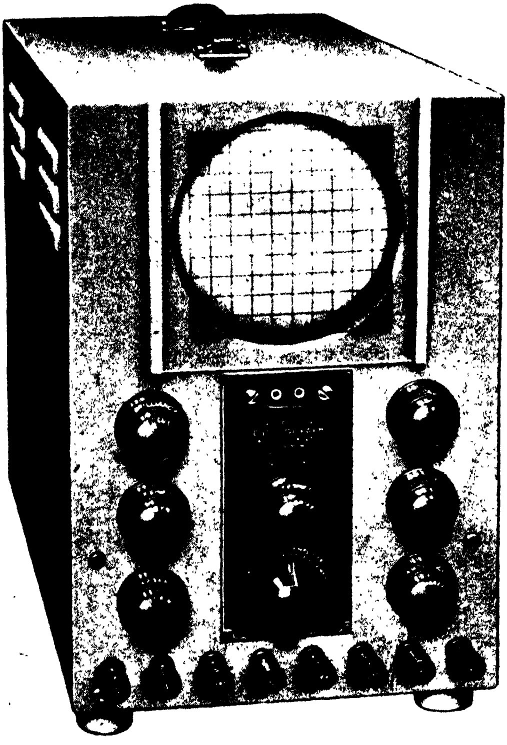

FIG. 43.—Double beam oscillograph by Cossor.

The problem of accommodating so many adjustments is solved, as shown in the figure, by the use of two knobs in tandem, of slightly different diameters, for six of the eight control points. A single-beam tube can, however, be used without any alteration of the set. In both cases trapezium distortion is avoided, since with the single-beam the amplifier is divided symmetrically on each side of the tube, and with the double-beam the effects are in opposite directions and hence cancel out. The amplifiers are also capable of being interconnected to give either high gain (4,000 times at from 10 to 100,000 cycles), or wide band operation (350 times at from 10 to 2,500,000 cycles).

Two automatic features should be mentioned, viz., brilliancy control at high time-base speeds, and frequency-compensated gain control, both of which make for greater efficiency and convenience. There is also a special winding on the mains transformer for providing a calibrating voltage. The tube screen has a diameter of 4½ in., and guides are provided for accommodating either the graticule as shown, or a camera attachment.

Examples of the work done by this instrument are to be seen in Figs. 27, 73 and 99.

TRANSIENT RECORDER. A glass tube oscillograph * has been specially designed by Standard Telephones Ltd. for recording single-sweep transients, and affords a good example of the capabilities with which this type has been endowed owing to improvements during the past six or seven years. It is shown assembled and ready for service in Fig. 44, and is able to record uncontrolled as well as controlled surges ; or, in other words, it will function even if the arrival of the surge is unexpected.

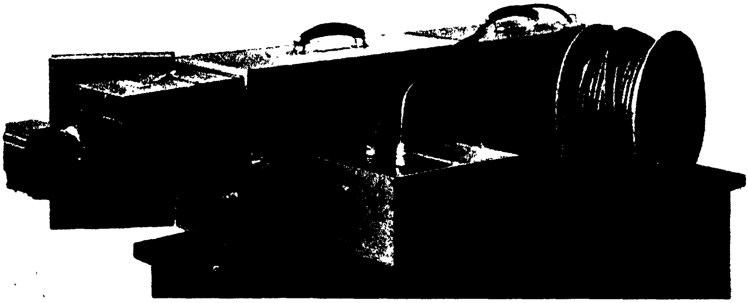

FIG. 44.—Transient recorder. (Standard Telephones and Cables Ltd.)

All the apparatus is contained in two portable cases, of which one houses the oscillograph and the other the mains unit, the two weighing 37 and 58 lb. respectively. Interconnection between them is rendered simple and expeditious by the use of corresponding plugs and sockets mounted on the back ends of the cases, which are assembled by merely pushing them together back to back as shown in the figure. The tube screen, 5½ in. in diameter, is concealed by the camera unit in the illustration ; which incidentally shows the delay cable and a small surge-generator set up ready for a determination.

The scheme for initiating the beam upon receipt of the impulse

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* See McGillewie, *Journal I.E.E.*, Vol. 83, November 1938 p. 657.

is shown in the left-hand and lower part of Fig. 45, which also includes the potential divider on the right and its connections to the focussing electrodes $A_1$, $A_2$ and $A_3$. A three-sphere spark gap on the left has its outer members energised at 2 kV above and below earth respectively, while the middle sphere is earthed through a resistance of about a megohm. The spacing is made just sufficient to prevent spark-over, so that the arrival of an impulse of either polarity at the middle sphere will cause half the gap to break down in a fraction of a micro-second, provided the voltage reaches about 500 volts. A complete breakdown of the whole gap follows without observable delay, sending a positive pulse from the middle sphere through $C_1$, $R_1$, $R_2$ and $C_2$ to the cathode K and through the decoupling condenser $C_3$ to earth.

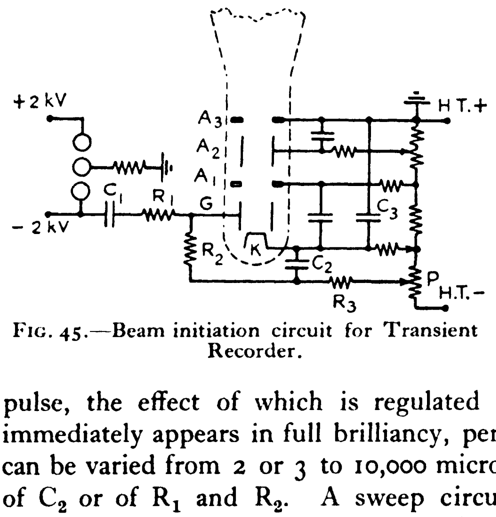

FIG. 45.—Beam initiation circuit for Transient Recorder.

Now the tube has been put into commission by switching on the voltage supplies, allowing the cathode to heat up to working temperature, focussing and adjusting the spot, and then adjusting the "grid" modulating potentiometer P until the beam just becomes invisible. This modulation is cancelled by the positive pulse, the effect of which is regulated by $R_1$ and $R_2$. The spot immediately appears in full brilliancy, persisting for a duration which can be varied from 2 or 3 to 10,000 micro-seconds by the adjustment of $C_2$ or of $R_1$ and $R_2$. A sweep circuit, broadly resembling that in Fig. 29, without the trip-plates, is also connected to the spheres.

The close control of the duration enables an unusually brilliant spot to be employed, which again brings high-speed transients within the range of both observation and photography. Accordingly an anode voltage of 5 kV is used. Examples of the high writing speeds that have been obtained from the instrument are given in Figs. 126 and 127.

SMALL PORTABLE SET. Simplicity and compactness have both been mentioned as advantages of the cathode oscillograph as compared with competing instruments ; but there are a number of purposes for which a lower degree of accuracy, together with even less bulk and elaboration, would be adequate than in the types that have so far been described. An interesting design of such a set, contained in a case measuring only 12 × 11 × 4½ in., was recently described by Macfadyen.* It is based

* See *Journal of Scientific Instruments*, Vol. 17, October, 1940, p. 249.

on the small " monitor " tubes having a 2½ in. screen, and its construction is given in complete detail in such a way as to enable an " amateur " to make it with a minimum of expense.

The specification includes the following :—

1. A.C. mains operation.
2. Linear time base, 20 to 10,000 cycles.
3. One single-stage amplifier, with a gain of seventy times.

Simplicity has been achieved by omitting all magnetic screening, and instead preventing interference by (*a*) placing the mains transformer coils under and coaxial with the cathode ray tube, (*b*) keeping the plate connections short, and (*c*) locating the amplifier input circuit as far from the mains supply circuits as possible. Convenience in viewing, as well as condition (*a*), have been secured by placing the tube diagonally in the case, with its screen occupying what would have been one of the upper angles. The set was shown in Fig. 38, p. 49.

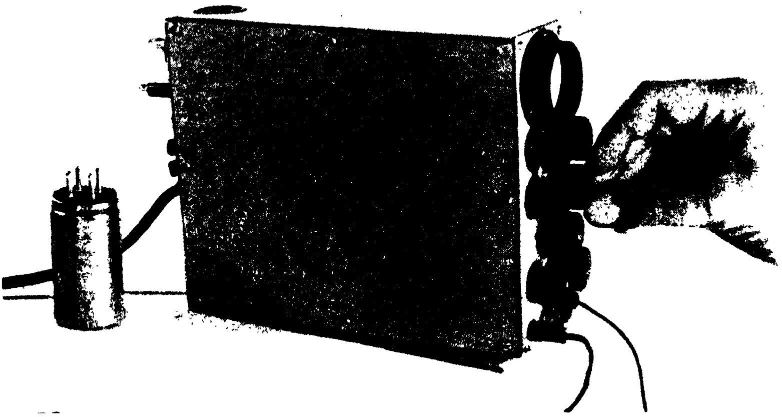

FIG. 46.—Miniscope miniature oscillograph (Salford Electrical Instruments).

There are four valves, of which the rectifier and the rest of the power pack components (except the mains transformer) are situated on a shelf above and behind the oscillograph tube. All the other parts are located on a raised deck below and in front of the tube, or on the adjacent front panel. These include the gas-filled relay forming the time-base discharge device, the constant current charging valve, and the amplifying valve.

It will be seen that an apparatus has been produced which can be readily carried in a small suitcase. Apart from its portability, its simplicity will encourage its use for purposes which might be considered

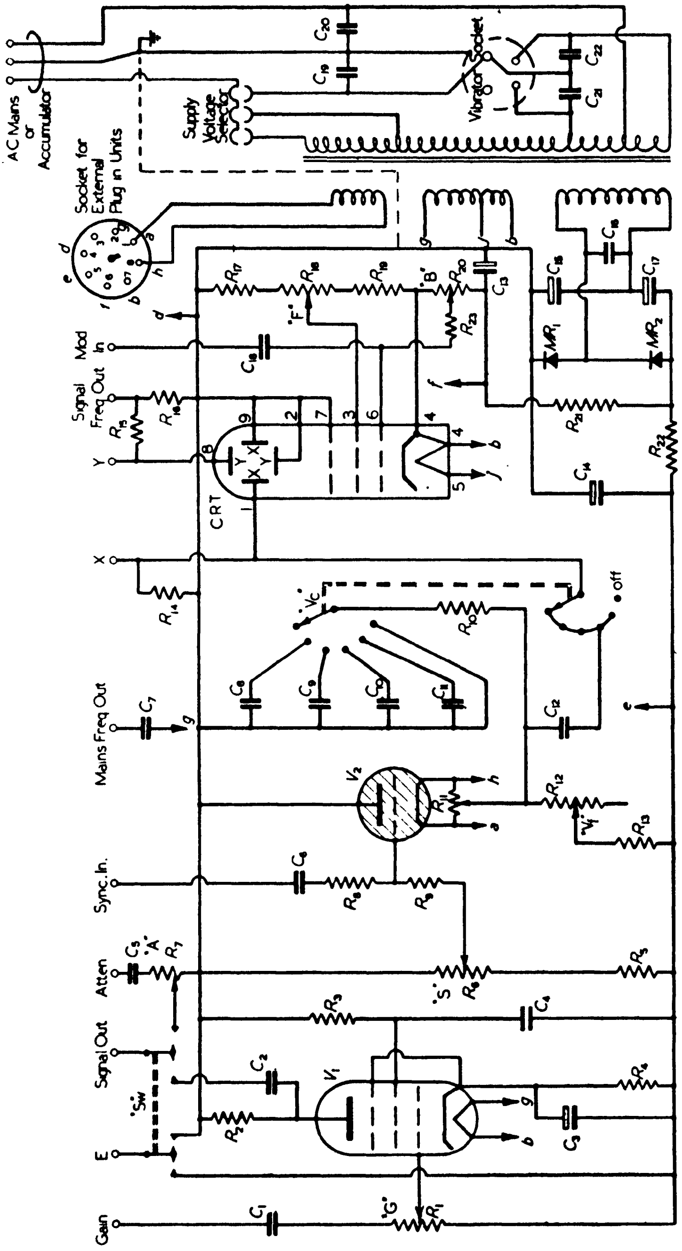

FIG. 47.—Circuit diagram of miniscope.

too unimportant to justify the fetching and connecting up of a larger set.

MINIATURE SET. The "Miniscope,"* a model made by Salford

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* Trade mark registration applied for.

Electrical Instruments, is so small that it may be carried in an ordinary attache case with other articles, and is shown in Fig. 46. Compactness has been secured by the use of miniature valves and a G.E.C. E4103/B/4 " monitor " cathode-ray tube with a screen diameter of only 1½ in.; but normal accuracy is achieved by the reduction of the spot size in proportion to that of the screen. The diagram forming Fig. 47 shows the arrangement of the various parts.

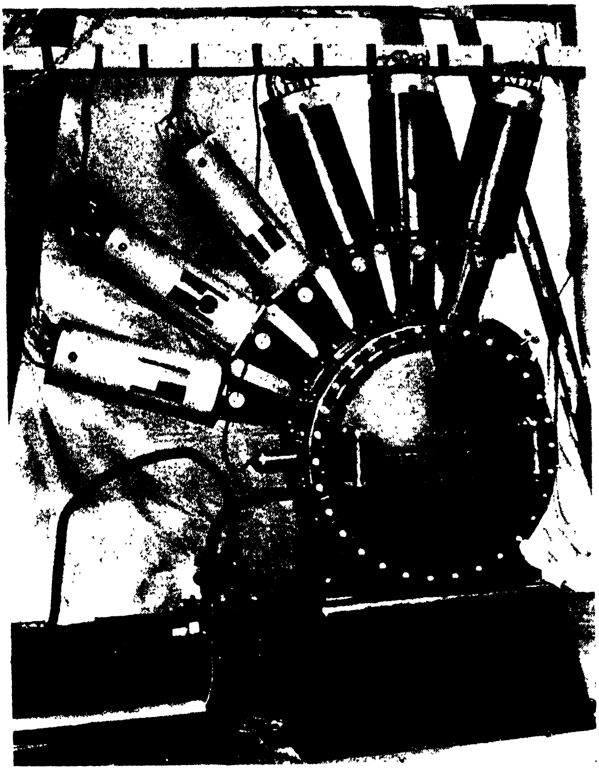

FIG. 48.—Six-element E.R.A. Cambridge sealed-off oscillograph.

The instrument may be operated from A.C. voltages of 110, 180 or 230 volts; while a separate small " vibrator " unit (shown at the left of Fig. 46) may be plugged into the back of the instrument, enabling it to be supplied from a 6-volt battery capable of giving about 3·5 amps. Metal rectifiers in " voltage-doubler " connection reduce the number of valves required to two, viz. an Osram CV2 gas-filled triode for triggering the time-base, and an Osram Z90 tetrode as amplifier. The seven control knobs are for brilliancy (B), focus (F), horizontal amplitude (S), vertical gain (G), vertical attenuation (A), fine ($V_F$) and coarse ($V_c$) adjustment of sweep frequency. Values up to 20 kc/s. are given by the two last, the frequency response of the amplifier being quite flat from 100 to 10,000 c/s. The maximum gain of the amplifier is × 430.

GLASS-TUBE DRUM MODEL. The utility of the glass-tube oscillograph has been greatly extended by means of a design which has been brought into being jointly by the Electrical Research Association and the Cambridge Instrument Co. Its original purpose was the recording of transients caused by short-circuits at various points in a supply network, calling for a portable instrument which could be transported in a trailer drawn by a car or delivery van. A number of independent traces were required to be taken simultaneously, while the requirements as to speed were the same as for the metal-tube model described in Chapter II, viz., the distinct recording of frequencies reaching 100 kc/s. or even 200 kc/s.

FIG. 49.—End view of oscillograph of Fig. 48 housed in trailer.

All demands were met by the instrument shown in Figs. 48 and 49. The same drum is employed as for the Cambridge metal-tube oscillograph, rotating at the same speed, and evacuated by means of the mechanical pump seen on the left. Six glass oscillograph tubes are mounted round the periphery at longitudinal spacings of about 4 in., and staggered laterally so as to record comfortably on a film 3 in. wide. At the same time, provision was made to increase the number to twelve, recording on the full width of 5 in. provided by the drum. Between screens and film are photographic lenses having an aperature of f/1.4 and a focus of 1 in., giving a reduction of 10 to 1. The object of evacuating the casing is merely to obviate air friction and thus economise in driving power, and consequently only the mechanical pump on the left of the drum in Fig. 48 is required. Even this pump has been omitted in a recent model.

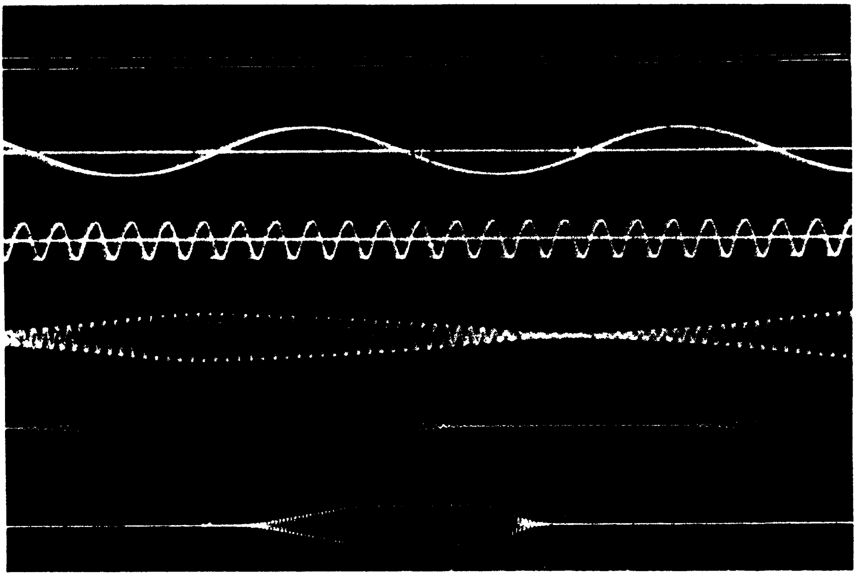

FIG. 50.—Part of record by six-element oscillograph shown in Figs. 48–49.
Traces are :

1. 50 c/s. and zero line.
2. 2 kc/s ,, ,,
3. 20 ,, ,, ,,
4. 50 ,, modulated at 1 kc/s.
5. 100 ,, ,, ,,
6. 200 ,, ,, ,,

Time scale
1 cm. = 100 μs.

An example of the work done by the above model is given in Fig. 50, where the six traces consist of waves of steadily increasing frequency, reaching the high value of 200 kc/s. A further example from actual practice is the restriking transient forming Fig. 122.

M.V. METAL-TUBE MODELS. Finally, a further pattern of metal-tube instrument will be described which, like that shown in Fig. 4, is made in both the drum and fixed-film patterns, and possesses a number of distinctive features. It was designed by Burch and Whelpton and made by Messrs. Metro-Vickers ; and is shown in its single-phase fixed-film form in Fig. 51. The more elaborate three-phase drum pattern is illustrated in the foreground of Fig. 52, in front of the single-phase Cambridge instrument, and will be more especially the subject of the present description.

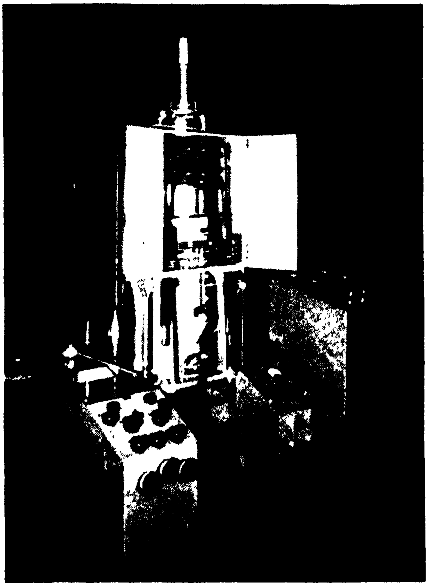

FIG. 51.—Metro-Vick metal tube oscillograph with stationary film, designed by Burch and Whelpton.

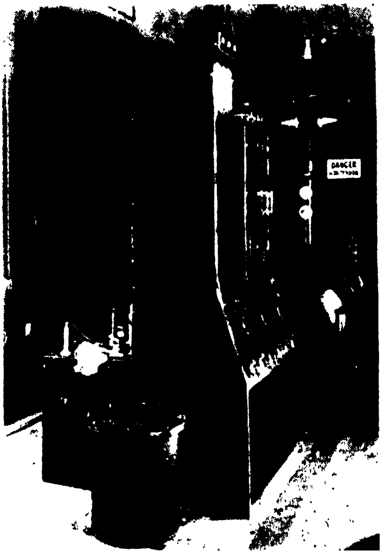

FIG. 52.—Three-phase and single-phase metal-tube oscillographs at the G.E.C. high-power test station.

The M.V. model is smaller than the Cambridge, and employs an anode (accelerating) voltage of 15 kV as compared with about 45 to 60 kV for the latter. There is a separate tube for each of the three beams, and the whole instrument is quite self-contained ; for the complete pumping equipment is housed in and on the base compartment of the cubicle. As the latter is composed of steel, efficient screening is provided against external magnetic fields, and there is hence no need for any special lining of the room walls. The drum is 11 in. in diameter by 13 in. long, and is capable of rotating at 6,000 r.p.m., giving a film speed of the same order as the larger model.

Instead of relying upon a stuffing box for enabling the drive to be taken into the vacuum, the rotor of the induction motor is located inside the evacuated casing, being enclosed by a tubular extension of high resistance nickel-copper alloy. The stator fits closely over the outside of the tube, and very little power is required even for this relatively long drum, owing to the complete absence of air friction.

Each of the discharge-tubes, which are seen emerging from the top of the cubicle, is fitted with a separate milliammeter and a needle-valve air leak. The latter does not, however, communicate with the atmosphere, but with a common pipe leading from a special exhaust pump and fitted with a further leak and a Geissler tube. As the pressures on the two sides of the first leaks are not very different, fine adjustment of the tube vacuum is easily obtained. Two stages of mechanical rotary pump are used, followed by two oil-diffusion pumps ; the avoidance of mercury rendering several complications unnecessary, such as solid $CO_2$ traps for preventing mercury vapour from getting into the vacuum.

Examples of the work done by this model are seen in Fig. 121.

**Recurrent Surge Instruments.** In connection with most of the glass-tube instruments that have been described, provision has been made in the shape of a repeating time-base for recording a cyclic wave by exactly superposing successive screen images upon one another, both observation and photography being greatly facilitated thereby. A method has recently been evolved by K. J. R. Wilkinson, of the B.T.H. Co., whereby the same facilities can be extended to certain single-transient effects, by causing them to occur repeatedly and in synchronism with a repeating time base.

The principle consists of the cyclic generation of voltage surges of the same shape as those due, for example, to lightning, and applying them to the apparatus or circuit concerned. By means similar to that employed for the repeating time base itself, the surge is made to trace its complete wave from 50 to 1,000 times per second, and the resultant voltage fluctuations are clearly and accurately indicated, although upon a reduced scale relatively to the original phenomena.

The method has been applied to two determinations for which elaborate and massive apparatus were previously essential. These are, first, the effect of voltage surges in producing large potential differences in transformer (and other) windings ; and secondly, the wave-form of the voltage which appears at the contacts of a circuit-breaker interrupting a short circuit, and which tends to restrike the arc after a zero pause. In both, the surge is generated by a gas-filled relay (or thyratron)* fed from the same transformer in the " mains

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* See N. Rohats, *General Electric Review*, 1936, Vol. 39, p. 136.

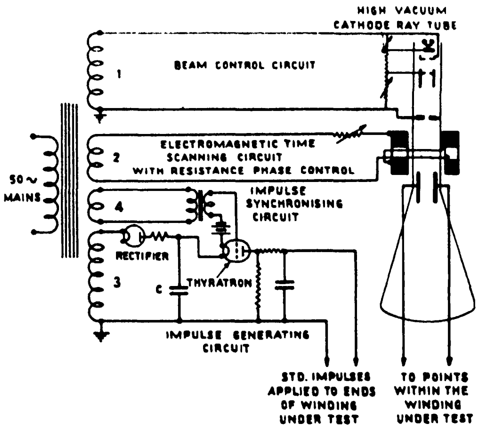
HIGH VACUUM CATHODE RAY TUBE
BEAM CONTROL CIRCUIT
1
ELECTROMAGNETIC TIME SCANNING CIRCUIT WITH RESISTANCE PHASE CONTROL
2
50 ∿ MAINS
4
IMPULSE SYNCHRONISING CIRCUIT
RECTIFIER
3
C
THYRATRON
IMPULSE GENERATING CIRCUIT
STD. IMPULSES APPLIED TO ENDS OF WINDING UNDER TEST
TO POINTS WITHIN THE WINDING UNDER TEST

FIG. 53.—Circuit of recurrent surge generator with 50 c.p.s. scan.

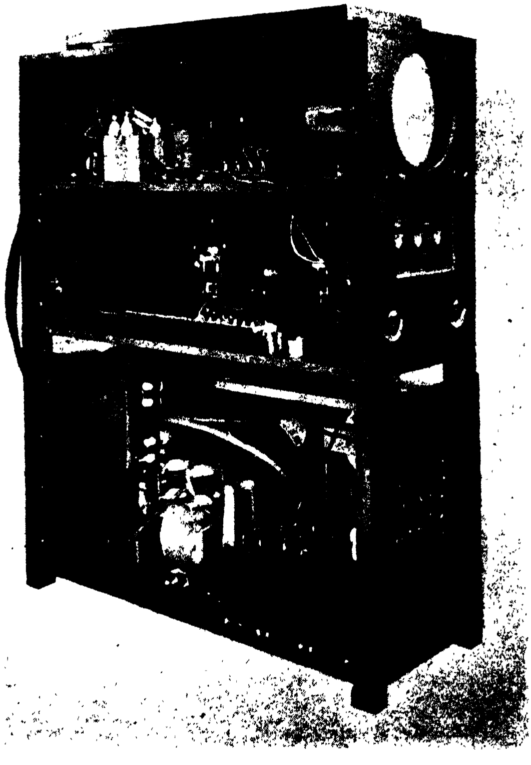

FIG. 54.—Recurrent surge oscillograph by B.T.H.

unit " as provides the power supply for the cathode oscillograph itself. As, however, the peak voltage of about 500 volts is already in existence, the function of the relay tube is to act as a switch capable of causing a practically instantaneous increase from zero to the full peak voltage while carrying its full surge current. This is effected by virtue of its rectifier characteristic.

**Recurrent Surge Oscillograph.** The circuit of the recurrent surge generator and oscillograph in its original form is shown in Fig. 53, while the instrument itself is illustrated in Fig. 54. On the left is the feeding transformer, the primary of which is supplied from the 50-cycle mains. Four secondary windings operate all the controls, and as their voltages are initially in step, synchronism between the various functions is not difficult to bring about.*

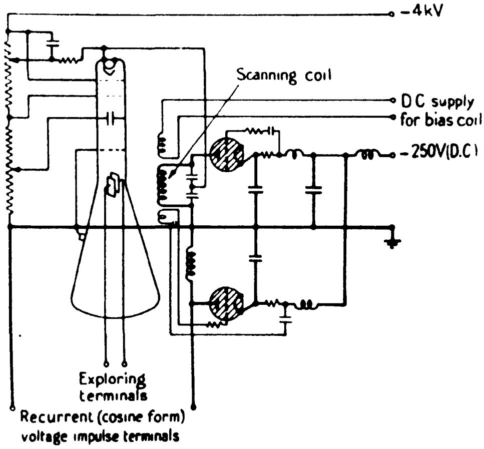

FIG. 55.—Recurrent surge generator, revised form, with 1,000 c.p.s. scan.

A high-voltage (3 kV), high-vacuum oscillograph tube is used, of the type devised for television receivers ; and secondary circuit No. 1 supplies all the voltage needed for generating, releasing, and focussing the beam, which is emitted for a portion of each negative half-cycle. Circuit No. 2 provides a time-sweep by means of electromagnetic deflecting coils, constituting a sine-wave time base. Since the deflecting force is strong enough to sweep the beam far off the screen, the small fraction of the sine-wave that is actually employed in the record is sensibly a straight line, its duration being only from 50 to 200 microseconds. A variable resistance is included in the circuit to adjust the speed of the scan, affording control of the image position.

The third circuit, shown at the base of the figure, is responsible for generating the surges. A condenser C is charged by the rectifier tube, and the energy thus stored is released by the gas-filled relay. The latter actually constitutes a small grid-controlled mercury vapour rectifier, and the instant for its operation is decided by the application to the grid of the synchronising impulse from Circuit No. 4. A " peaking " transformer is interposed in its path, making the impulse current much sharper and effectively ensuring that all the surges are exactly superposed on one another. An oscillator for adding fast and slow timing waves to the record is included, but not shown in the diagram.

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* See K. J. R. Wilkinson, " Recurrent Surge Oscillographs," *J. I. E. E.*, Vol. 83, March 1938, p. 663.

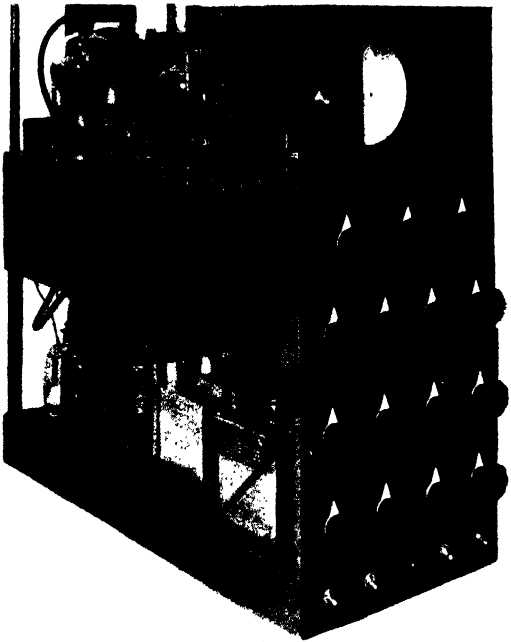

FIG. 56.—E.R.A. recurrent surge oscillograph.

In a recent modification shown in Fig. 55, the time-sweep is actuated by an oscillating current generated in a circuit tuned to a frequency of 1,000 c/s. Twenty times as many surges are therefore produced in a given time, and the image is correspondingly brighter. Certain other modifications have also been introduced without departing from the main principle, the chief change having already been mentioned ; but on account of its simplicity, the author has retained the original diagram (Fig. 53) to illustrate the general working of the scheme.

Records taken with the revised apparatus are shown later in Figs. 105 and 106.

E.R.A. RECURRENT SURGE OSCILLOGRAPH. An apparatus designed by E. L. White of the B.E.A.I.R.A. is shown in Fig. 56, which carries out the same functions as the above, and has the additional feature that it traces three waves upon the screen simultaneously. Examples of its work are shown later in Figs. 107 and 109, in which the phenomenon under investigation, timing wave and zero voltage could all have been recorded at the same time, and shown as clearly and as sharply as in the case of a single-wave instrument. The oscillograph is normally supplied from a 50-cycle source, and the three traces are repeated 50, 50, and 100 times per second respectively.

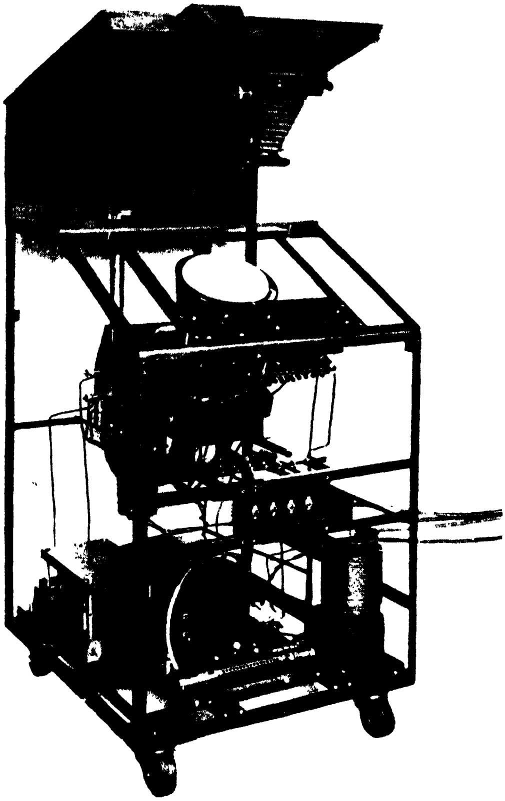

FIG. 57.—Restriking voltage indicator by B.T.H., with sides of cabinet removed.

The sweep speed can be varied over a wide range, the limits being 200 and 0·5 mm./$\mu$s, the former of which is equal to 200 km. or

125 miles per second. A very open time-base is achieved at the higher speeds, exemplified by the record in Fig. 109, where the whole wave represents only a half-cycle at 1 Mc/s. To obtain so sharp a trace as in these figures, an accuracy of tripping of the order of $10^{-8}$ sec. is necessary.

The instrument contains six gas-filled triodes, and a Standard 4063 YB cathode ray tube having a final anode voltage of 5 kV. When the built-in recurrent impulse generator is in use, the time-base frequency is 100 c/s, the tripping pulses being obtained by means of a full-wave rectifier operating as a frequency doubler and supplied from the 230-volt 50 c/s. mains. Two of the G.F. triodes are ionised in alternate sweeps, and form an automatic switch connecting in the two signals in turn, their return trace forming the zero line. Thus the three traces can be recorded simultaneously ; but as the return trace is not as sharply focussed as the others, it is usually suppressed by grid modulation when the figure is being photographed, and the zero voltage trace recorded positively.

Chopping of the waves can be effected at any point. The instrument can readily be used to record uncontrolled surges from an external source. As in the B.T.H. equipment the components are mounted upon an upper and a lower chassis, which can be separated for transport purposes and reasembled in a few minutes.*

**Restriking Voltage Indicator.** The object of the second apparatus, illustrated in Fig. 57, is to inject a square-fronted current wave into the system under test, across the open contacts of the circuit breaker controlling that system, as shown in Fig. 58. It will not be difficult to see that such an arrangement will be equivalent to the production of a similar wave by the opening of the contacts.

Now a surge of this description, but on a much greater scale, is caused by the rupturing of a short-circuit ; and as either will give rise to an oscillation at the natural frequency of the circuit, the resultant wave front will be of the same shape and therefore have the same slope in both instances. In other words, the rate-of-rise of restriking voltage, as well as the components in the wave, will be faithfully recorded by the indicator in all but

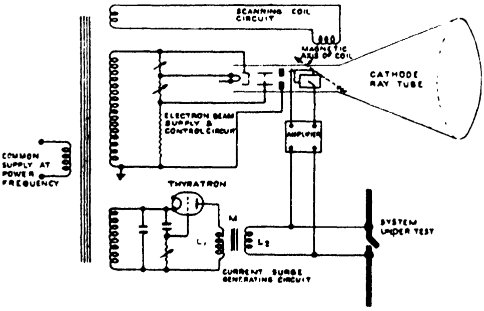
SCANNING COIL CIRCUIT
MAGNETIC AXIS OF COIL
CATHODE RAY TUBE
ELECTRON BEAM SUPPLY & CONTROL CIRCUIT
AMPLIFIER
COMMON SUPPLY AT POWER FREQUENCY
THYRATRON
M
L1
L2
SYSTEM UNDER TEST
CURRENT SURGE GENERATING CIRCUIT

FIG. 58.—Circuit of restriking voltage indicator.

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* See "A new High-Speed Recurrent Surge Oscillograph," *Jour. Sc. Insts.*, Vol. 20, August, 1943, p. 125.

magnitude; and as the restriking wave merges into the recovery voltage, a knowledge of the latter enables the correct value of the former to be calculated.

A square-fronted current wave may be obtained from a voltage wave of similar shape (as shown in Fig. 105) by applying the voltage surge to the primary of a transformer with a short-circuited secondary. Hence the requirement is met by the use of a mutual inductance, M in Fig. 58, with the plate of the thyratron connected to the primary $L_1$, the constants being so arranged that the impedance at the primary terminals is high compared with that of the secondary circuit.*

Since a few hundred volts are required to give an adequate deflection of the beam, and since a surge generator to produce such a voltage in a normal supply system would require an impracticably high kVA capacity, a surge of only a few volts is actually generated, and the voltage wave form is then amplified as shown in the figure to provide a satisfactory image.

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* See Trencham and Wilkinson, "Restriking Voltage and its importance in Circuit Breaker Operation," *J.I.E.E.*, Vol. 80, May 1937, p. 460.

## CHAPTER FIVE

# SINGLE DEFLECTION READINGS

A list of the advantages possessed by the cathode ray oscillograph over its electro-magnetic competitor in particular, and other measuring instruments in general, was afforded at the end of Chapter I. Many of these new features have given wonderful new powers to the experimenter, such as writing speeds far exceeding even the most sanguine expectations of only a comparatively few years ago. They are, however, by no means all used for every test. In some cases, for example, a high writing speed is not required ; while again, other advantages may render the instrument worth using even when no cross feed at all is to be employed.

The various applications will therefore be dealt with more or less in the order of their elaboration. They can be divided quite naturally into the following six groups :—

I. Those requiring only a single pair of deflectors : the tube functioning merely as a voltmeter or ammeter.

II. Those in which two similar quantities are balanced or compared, such as two voltages or frequencies, by being applied to the two pairs of deflectors respectively.

III. Those in which a repeating time base supplies the horizontal travel, enabling the indication to be prolonged as much as desired.

IV. Those in which a transient occurs once only, requiring a single-sweep time-base.

V. Those in which neither variable is time.

VI. Those in which one of the variables is mechanical pressure ; the other consisting usually of time or displacement.

The author proposes to consider these groups of applications in turn, describing typical examples of each, and stating the advantage possessed in each case by the cathode tube over other methods.

**I. Applications Requiring a Single Deflection.** If only a single pair of deflecting plates or coils is used, the oscillograph functions directly as an ammeter or voltmeter. At first sight one might be tempted to query the need for using so advanced an apparatus in this way, when there is such a large variety of indicating meters available which require no other preparation than connecting up the leads. But even so, the cathode oscillograph has several valuable advantages for the purposes in question. To begin with, there is a complete absence of sluggishness and damping troubles. Then the determinations are not affected by changes of frequency or temperature. The risk of damage through over-voltages (or over-currents) is reduced almost to zero, as a peak of many times the scale reading merely deflects the spot off the screen. For many purposes its greatest advantage is the very high input impedance, involving only a minute loading effect upon the voltage which is being measured.

In general, the tube used for the present purpose would be provided with the usual two sets of deflecting means, of which only the one would be employed. When a pair of deflector plates is not in use, it is important that they be connected together and to earth, in order to obviate their receiving a charge in some way which may influence the results. The use of magnetic deflection coils for recording A.C. voltages is not usually recommended owing to the variation in the reading introduced by the frequency, though this method may be very useful for dealing with currents.

Both D.C. and A.C. measurements are made with equal facility. In the former case, the polarity is indicated and the trace on the screen consists of a single spot ; while in the latter, the reading is a luminous line representing twice the peak value of the voltage or current. As with ordinary indicating meters, a shunt is needed when currents have to be measured by means of the deflecting plates, and care is then usually necessary to avoid inductance. When this is so, a " bifilar " or " hairpin " design of resistor is generally employed, the resistance wire or strip being doubled on itself with a minimum thickness of insulation between the two limbs.

Although the oscillograph itself will deal effectively with both D.C. and A.C. quantities, there are several reasons why it is most often used for the latter. The D.C. moving-coil meter is a more convenient and accurate instrument than an A.C. meter. It has an open scale, is very well damped, is capable of greater precision than its A.C. counterpart, imposes a smaller load upon the voltage or current source being measured, and is free from frequency errors. Further, the usual amplifiers cannot be used in connection with D.C. oscillographic measurements if the constant D.C. component is to be retained, since neither transformers nor condensers will transmit direct currents. Hence the leads have either to be taken directly to the deflector plates without amplification, or a special type of amplifier would be necessary which has certain limitations.

To determine the quantitative value of the indication, it would be possible to measure the length of the line (or deflection of the spot in the case of D.C.), and calculate the result with a knowledge of the sensitivity of the oscillograph in volts per inch, together with the gain factor of the amplifier ; and if this is done, the product must be divided by $2\sqrt{2}$, or 2·83, to give R.M.S. values in the case of A.C. But great care would be needed to obtain anything but an approximate result by this procedure, and calibration by means of a known e.m.f. is a more certain and accurate method. Whichever way is adopted, however, it is necessary to be sure that the amplifier has a linear characteristic over the range of frequencies in question. Fortunately the amplifiers used with cathode ray oscillographs and usually built into the case give a sufficiently linear response up to at least 100 kc/s. when operated at full amplification. For reduced gains the characteristic is nearly linear, but for very accurate work it may be advisable to check this point. The input impedance, including internal amplifier, is usually of the order of half a megohm ; while the capacity of the deflector plates (which is mostly due to the " lead-in " means) will never exceed 10 micro-microfarads.

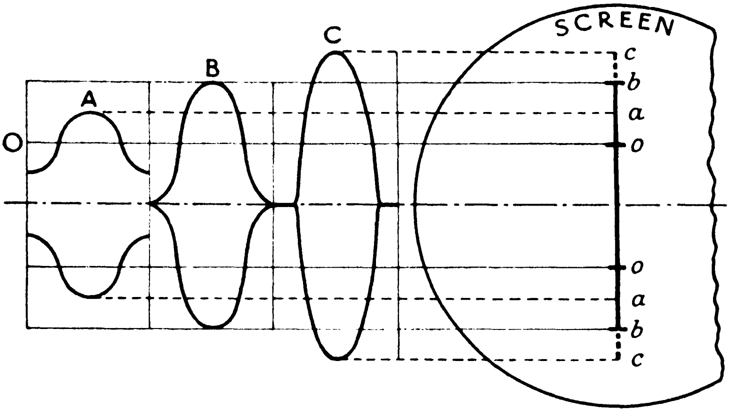

FIG. 59.—Modulated wave.*

Many applications of " straight " voltmeter measurement will probably suggest themselves ; but typical cases of special interest will be described.

1. BROADCAST MONITOR. A practical example of the use of the oscillograph as a voltmeter is for " monitoring " broadcast transmissions, for which the very small loading effect is a considerable advantage. The trace on the screen affords an easy means of keeping a continuous check upon the output volume, the speech voltage being simply connected to the terminals belonging to one pair of plates. A similar purpose is served in connection with broadcast television, and also gramophone recording.

2. MODULATION CHECK. A modulated wave, as used for the transmission of wireless telephony, consists of a " carrier " of radio frequency, the amplitude of which is caused to vary so that the upper and

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* An actual oscillogram is shown in Fig. 75 (see p. 94).

lower envelopes are mirror images of each other and constitute the audio-frequency signal. Such a wave is shown in Fig. 59, in which it is evident that the modulation increases in effectiveness with increasing amplitude of the envelope until the latter reaches the axis, after which the signal wave becomes distorted.

It is frequently desirable to keep a continuous check upon the degree of modulation, to prevent distortion occurring during the louder passages, and a cathode tube arranged for single deflection forms a convenient method. The limits of the plain (unmodulated) carrier wave are marked upon the screen, being the extremities of the luminous straight line traced under these conditions. Further marks are then made corresponding to double the above length ; and over-modulation is indicated by the line extending beyond the outer marks.

3. THICKNESS INDICATOR. A further example of single deflection practice is afforded by the electronic apparatus for rapidly and accurately gauging thickness, the principle of which is indicated in Fig. 60. The articles to be gauged may be inserted between a flat surface and an upper contact piece, the movement of which is magnified by a lever having the moving plate of an air condenser attached to its far end. Capacity variations so produced are applied between grid and anode of a valve V, providing a " feed-back " and thus controlling the amplitude of the consequent oscillations. This is measured by the oscillograph, and over the desired range is sensibly proportional to the thickness of the specimen. The earthing of the unused deflector plates should be noted.

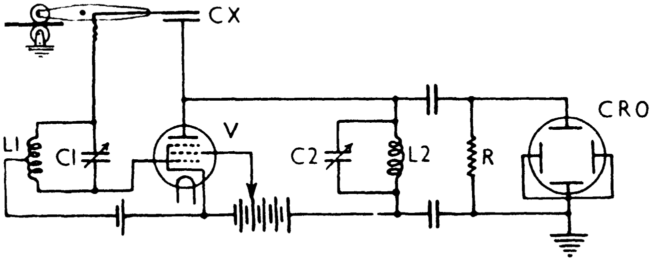


FIG. 60.—Circuit for thickness gauging.

Perhaps the most useful application of the above principle is for the continuous gauging of a strip as it comes from the rolls, forming a check upon its uniformity. For example, paper strip for the manufacture of condensers must have a very constant thickness, and presents great difficulty in quick measurement by hand micrometer. Similarly high-permeability steel for the magnetic circuits of small transformers and relays requires continuous gauging. In such cases the fixed surface forming the lower datum and the upper " contact " piece would each be replaced by a roller as shown in the figure, operating the reaction condenser as before. The oscillograph screen would be provided with a scale calibrated in $10^{-4}$ in. divisions, which would be checked against a micrometer at the beginning of the process.

A pentode valve is of advantage since it is not subject to independent oscillation. $L_1C_1$ and $L_2C_2$ will be recognised as the tuning circuits for the grid and anode respectively, and the output terminals are taken through fixed condensers to the deflecting plates, which are shunted by the leak resistance R.

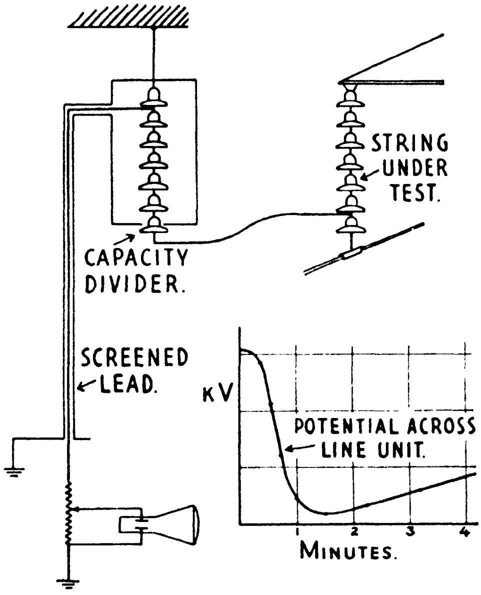


FIG. 61.—Thompson's method for observing the drying-out of line insulators during wet weather. The curve on the right shows typical variation of kV drop across a single link.

4. DRYING-OUT OF E.H.V. INSULATORS. The design of insulator strings for extra-high-voltage transmission is complicated by the disturbing effect of surface moisture upon the distribution of voltage along the links of the strings during times of fog or rain. Normally the voltage falls regularly, though not equally, from the link at the line end to that at the support ; but when the upper surfaces are wet, the regularity is upset by the effect of indeterminate conducting films. At one moment nearly half of the links may be practically out of action, their share of the voltage being distributed among the remaining units ; but the leakage current through the film of moisture is causing it to dry off rapidly, the process accelerating as the resistance of the liquid path increases. A short time afterwards the " resting " links will have resumed duty, and others have gone into temporary retirement ; as exemplified by the actual volts-drop/time curve in Fig. 61.

This process was studied by W. G. Thompson in 1935, by means of the cathode oscillograph. Atmospheric fouling and violent rain were reproduced as fully as possible in the laboratory, and the tests carried out as shown in Fig. 61 ; but exactly the same procedure could have been adopted at an actual line, if one had been available. The voltage-drop across the link under test was connected across a capacitance potential-divider consisting of a standard insulator-string suspended from a cross-arm and shielded from the spray by a cylindrical metal screen. A connection was taken from the link at the earthed end to the oscillograph through a screened down-lead, ending in a potentiometer resistance. Then the violent fluctuations of voltage across the link were faithfully revealed by the instrument, including not only the broad transition from the conducting to the insulating condition and *vice versâ*, but also the high-frequency oscillations as the individual drops or patches of water dried out. Such a performance was well beyond the capabilities of an indicating meter, both on account of sluggishness and liability to damage through over-reading.

5. ARC VOLTAGE. The value of the rapidly fluctuating voltage due to some arcs can only be measured correctly by the cathode oscillograph. Such measurements have frequently to be made in connection with tests upon large rectifiers, the following example being derived from the process of developing one on the gas-blast principle. A single alternation of the applied voltage is shown in Fig. 62, and the effect of the blast is seen in the suppression of the positive half-cycle AB, of which only the small arc voltage is able to persist. The object of the test was to ascertain the value of this arc voltage.

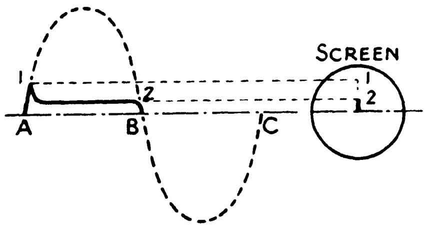


FIG. 62.—Arc voltage test

First, the negative loop BC was prevented from affecting the oscillograph by connecting a rectifying valve in series with the latter ; so that the deflection could be adjusted to give a full screen reading for the arc voltage. The requirement was hence the measurement of a succession of positive half-cycles of the form illustrated. If any kind of indicating ammeter were employed, it would read the R.M.S. value of the loops and spaces instead of the peak value as desired. Instead, a line is shown on the screen consisting of a bright spot representing the flat part of the voltage wave, with a faint but quite visible upward extension indicating the initial peak, thus affording all the information desired.

6. D.C. VOLTAGE MEASUREMENT. A typical example of D.C. voltage measurement is the testing of spark-quenching circuits. When a current flowing in an inductance is broken, such as that in the magnet coil of an automatic telephone switch or in the choke coil of a smoothing

filter, a voltage peak occurs which may have to be suppressed by means of a shunt circuit usually consisting of a condenser and resistance in series. The effectiveness of the arrangement provided is tested by connecting the pair of deflector plates across the break as shown at A in Fig. 63 and noting the deflection of the spot when the contacts part. Calibration is effected by means of a steady voltage.

In this case a meter is ruled out by two separate considerations. First, its operating coil would form a second shunt to the contacts and greatly reduce the voltage peak ; and secondly, its inertia would prevent it from recording such a transient. The Duddell oscillograph would also be invalidated by the first condition.

7. CURRENT MEASUREMENTS. The indication of direct currents has been mentioned as the least common test made by means of single deflection ; but there are cases nevertheless in which the cathode oscillograph forms the appropriate measuring agent. Examples are the surge current flowing when a power pack containing a smoothing condenser is connected to a radio receiver which is provided with a condenser for the same purpose ; and the current which is taken by a quench-spark circuit as described in the last section when the current is made, and which the resistance in the shunt circuit is intended to limit. The arrangement of the latter test is shown at B in Fig. 63.

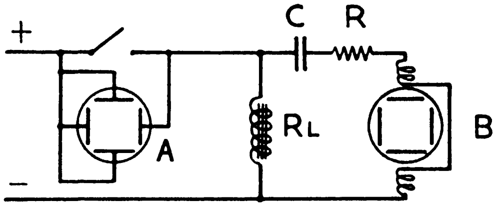


FIG. 63.—Use of cathode oscillograph at A, to measure voltage peaks across relay winding $R_L$ when fitted with quench-spark circuit CR ; and at B, to measure current rush on making circuit.

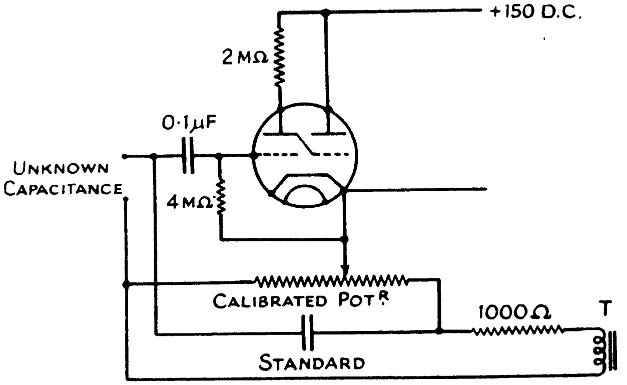
*N.B.*—The plates in B would be all connected together.

The above is an instance where magnetic deflecting coils are appropriate because of their negligible impedance.

8. MOTOR STARTING PEAKS. Prior to the introduction of the cathode oscillograph, there was no accurate visual method of measuring the current peaks of a D.C. (or A.C.) motor during the operation of starting. The recording ammeter gave only an approximate result owing to its considerable inertia and friction ; and the electro-magnetic oscillograph is too inconvenient for use as a reading instrument. But the cathode ray tube, provided with a paper strip attached to the screen for use as a scale, answers all requirements. It is especially convenient

when a series of tests is being made for the purpose of adjusting the resistance steps to give equal peaks, or other starting characteristics.

9. TONE CONTROL. The process of tone control in a receiver consists of altering the relative volume of the higher audio frequencies as compared with the lower, for example by by-passing a greater proportion of the former through a shunt condenser and variable resistance. When it is desired to test a given tone control, the different input frequencies are fed into the stage at a constant amplitude or voltage, and their respective attenuations are measured by means of the oscillograph. Owing to the very small amount of power available, as well as the high frequencies concerned, no ordinary voltmeter could hope to give satisfactory results.



A.C. bridge, arrangement using magic eye as detector.

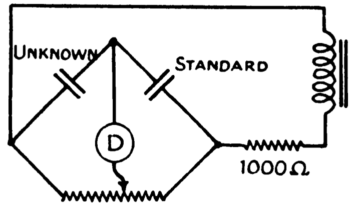


FIG. 64.--A.C. bridge basic circuit.

10. GALVANOMETER. It will have been evident that the cathode ray oscilloscope is well adapted for use as a sensitive, portable, and deadbeat galvanometer, giving a null indication when a circuit is balanced. Examples of such uses are bridge methods for measuring impedances, such as the Wheatstone and the Schering, especially the much used " box " patterns. In both, the accuracy of the readings can be greatly impaired by poor sensitivity of the galvanometer, the dial of which is necessarily restricted in size for reasons of portability.

The cathode ray instrument possesses the great advantages that the power required to produce the deflection is nearly all supplied from an external source ; and also that the sensitivity is very easily adjusted. For null readings, only a small screen, such as 1 in. in diameter, is sufficient, since no harm is caused by the spot being deflected far beyond the screen limits.

11. MAGIC EYE. The small luminous-anode oscillograph known as the Magic Eye is in effect a single-deflection oscilloscope. It forms a galvanometer and can be calibrated to act as a voltmeter. But its most frequent use, except as a tuning-indicator for wireless sets, is as a sensitive detector for both D.C. and A.C. bridges, but especially the latter. For this purpose it is not so sensitive as the telephone, but is sufficiently so for most requirements, and is much less tiring to use.* It is at an advantage as compared with most electromagnetic instruments in that its greatest sensitivity can be given for voltages near to zero, whereas square-law detectors are least sensitive for low deflections.

A typical A.C. bridge circuit, for the measurement of capacity, is shown in Fig. 64, in which the general scheme is given by the small diagram and the detailed arrangement by the large one. In the latter, T represents the secondary side of a mains transformer giving 50 volts at 50 c/s.

By substitution of a standard resistor for the standard condenser, the bridge is suitable for measuring resistances up to very high values ; and it will also fulfil other functions of the Wheatstone bridge. Its operation is, if anything, easier than in the case of the latter.

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* See Astbury, " Balance Detectors for A.C. Bridges," *Jour. Sci. Instruments*, Vol. 17, 1940, pp. 30–31.

## CHAPTER SIX

# DIFFERENTIAL TESTS

In its most usual form, the cathode ray oscillograph is furnished with two pairs of electrostatic deflector plates, situated in planes at right angles to each other ; the standard method of representing one of these instruments consisting of four straight lines, $Px_1$, $Px_2$, $Py_1$, and $Py_2$, arranged as the sides of a square, but not quite in contact. Actually, of course, the two pairs do not adjoin each other, but one pair must of necessity be the nearer to the cathode and the further from the screen, and must therefore give somewhat the more sensitive results ; otherwise conditions are exactly the same for both, and their use is interchangeable.

Since there is this equality of function, the oscillograph may be employed to compare similar voltages or currents, or conditions that can give rise to voltages or currents, in much the same way as a beam-balance or other differential relay compares electrical quantities, or a pair of scales compares weights. Thus the instrument can indicate exactly when two quantities that should be similar, such as the input and output of an amplifier, actually are similar, or if not, to what extent and in what way they differ in phase or in magnitude. Typical applications of this nature will be described.

Certain obvious precautions are necessary in order to secure the most accurate results. First, conditions should be as far as possible the same for each pair of deflectors. Since amplifiers are liable to introduce a slight distortion, they should be used either for both pairs or not at all. But many of the comparisons are between quantities differing in magnitude or " scale " ; and as the indications are the most sensitive when the deflections due to each pair are equal, a potentiometer connected in one or in each circuit is often a decided advantage.

1. PHASE DIFFERENCE. Conditions frequently arise in which it is required to detect and measure any phase difference that may exist between two alternating voltages or currents. If the effect be considered of connecting two sine waves which are in step with each other to the two pairs of plates respectively, it will be realised that the spot will move backwards and forwards along a line diagonal to the rectangle formed by the total horizontal and vertical amplitudes, as shown in Figs. 65 and 66. If these amplitudes are equal, then the diagonal becomes that of a square, and is inclined at 45° to the horizontal. If the waves are not sine waves, the trace will still remain the same, however great their complexity, provided they are exactly similar

and exactly in step ; the only difference caused by the change of waveform being in the rate at which the speed of the spot varies when tracing the diagonal.

If, however, the waves differ in phase, then the spot will travel up and down by different routes, and a looped figure is the result. In the case of sine waves, it will be seen that a phase difference of 90° will open out the diagonal into a circle, round which the spot will travel with uniform speed ; while a difference of 180° will produce a diagonal again, but with the opposite inclination to the original line. Intermediate differences will give ellipses of corresponding widths, as

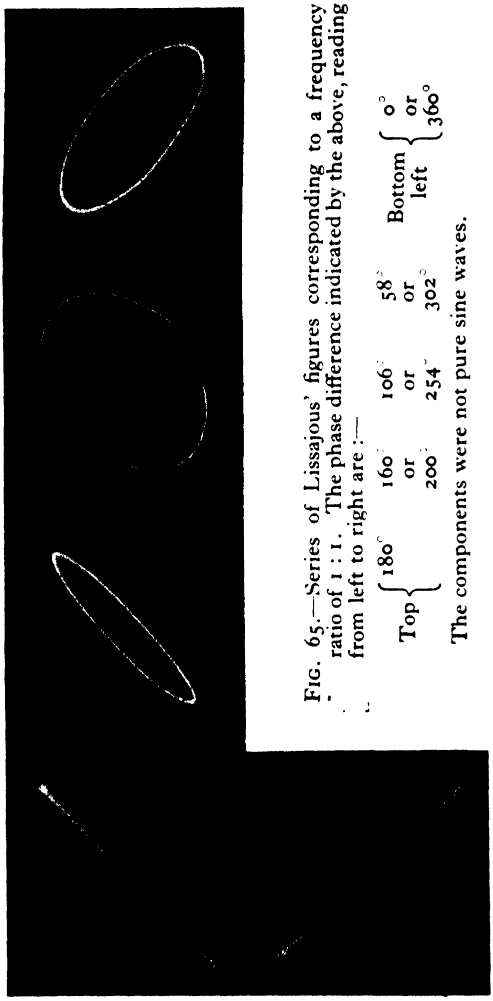

FIG. 65.—Series of Lissajous' figures corresponding to a frequency ratio of 1 : 1. The phase difference indicated by the above, reading from left to right are :—

Top { 180° 160° 106° 58° Bottom left { 0°
or 200° or 254° or 302° or 360°

The components were not pure sine waves.

exemplified by the series of oscillograms in Fig. 65. The phase angle corresponding to the various figures may be readily estimated by means of a relationship derived from Fig. 66, which also illustrates their formation. In this, the circle on the right represents successive positions of the vector XO, being the alternating voltage connected to the vertical plates of the oscillograph. Similarly, the circle on the left represents corresponding positions of the vector YO, the second alternating voltage, which is connected to the horizontal plates; these vectors being in phase when their numbers are the same. Then the positions of the spot are shown by the square figure ABCD, representing the oscillograph screen.

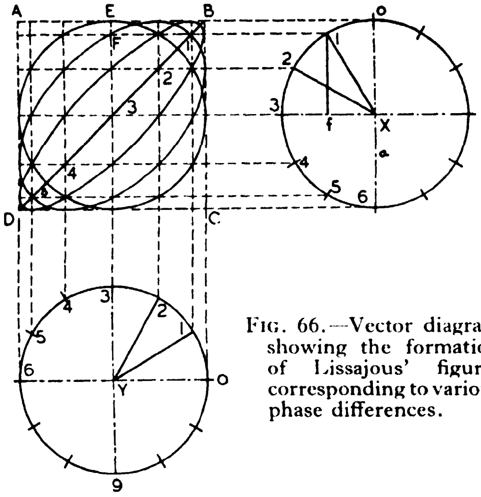

FIG. 66.—Vector diagram showing the formation of Lissajous' figures corresponding to various phase differences.

For example, if the vectors are both at O, the spot will be at B on the diagonal BD; and it will be seen that when both are at 1, 2, 3, 4, 5, and 6, the spot will occupy the successive positions 1, 2, 3, 4, 5, and D on the diagonal. If the X vector now advances 30° in phase relatively to the Y vector, it will be at 1, 2, 3, 4, 5, 6, when the latter is at 0, 1, 2, 3, 4, 5 respectively, and the spot will trace out the narrow ellipse passing through the next set of intersections, as shown. Similarly, if the vector X leads Y by 60°, the wider ellipse will be traced, and so on; the next step in the figure being the circle, for an angle of 90°.

In the figure, the radii of both circles have been made equal, of length $a$; and it will be seen that the major and minor axes of the ellipses both fall on diagonals of the square ABCD. Then the ellipse traced by the oscillograph may be used to determine the phase angle. Now the lengths of the major and minor axes can easily be measured from the figure on the screen. Let these be $M$ and $m$ respectively, and let the vector Y lead X by 60°, so that their respective starting positions are Xo and Y2.

Then $M = 51 = 2\sqrt{2}\,1f = 2\sqrt{2}a \cos 0X1 = 2\sqrt{2}a \cos (60°/2)$

and $m = 2\sqrt{2}a \sin 2X3 = 2\sqrt{2}a \sin (60°/2)$,

*i.e.* $m/M = \tan (60°/2)$;

or generally, if the phase difference $= \theta$,

$$m/M = \tan(\theta/2)$$

*i.e.* $$\theta = 2\tan^{-1}(m/M).$$

Thus the angle is found by calculating the ratio of the length to the width of the ellipse, looking up the angle whose tangent has this value, and doubling the angle so found. For example, the ratio width/length of the right-hand ellipse in Fig. 65 = 0·558. This equals tan 29°, and the phase angle is therefore 2 × 29°, or 58°. Reference to the diagram in Fig. 66 will show that the same ellipse could also be formed at a difference angle of 360° − 58° or 302°; or even by either of these values + 360° × *n* where *n* is a whole number. There will usually be no difficulty in deciding which is the correct value in practice.

The above holds good when the two voltages are of equal magnitude, and ABCD consequently a square; and there is little difficulty as a rule in adjusting the "gain" controls to give this result. If, however, an oblong figure has to be interpreted, the method can be deduced by imagining the whole figure ABCD expanded or contracted vertically, the various points moving outwards or inwards along the vertical lines. Then the proportionality still holds so long as the "width" and "length" are measured along the diagonals AC, BD of the oblong; but it should be noted that these lengths are not now the axes of the ellipse, or the true width and length, which in consequence of the obliquity have left the diagonals. For small departures from the square, little error is, however, introduced by simply measuring the apparent axes; but when the vectors differ considerably, the oblong corresponding to ABCD should be drawn round the ellipse, and measurements made along its diagonals.

An alternative method, which is of general application when the horizontal axis has been drawn, can also be deduced from the figure. The vertical line EF3 from the centre cuts the ellipse which has just been considered at F, *i.e.*, the point due to the vectors X1 and Y3, the phase angle thus being 1X3. Now $F3/E3 = 1f/1X = \sin\theta$; or $\theta = \sin^{-1}(F3/E3)$. A simple rule has thus been formulated, which obviously holds good even if the square becomes an oblong. Exemplifying the method, F3/E3 is found by measurement to be 0·866, and this is found from a set of tables to be sin 60°; thus the phase angle = 60°.

2. FAULT-TESTING OF WINDINGS. The principle responsible for the tests in the preceding section are directly applicable to the testing of coils and windings of electrical equipments, including even complete motors and generators. In these cases the winding under test is compared or balanced against a similar unit known to be in sound condition. As before, a diagonal straight line indicates a satisfactory result.

An example from practice is shown in Fig. 66A, which was obtained from a 1 h.p. induction motor stator, found to have a minor short-circuit in one phase. Since machines of this size are mass-produced, the method forms a suitable and convenient link in the chain of manufacturing operations.

3. SYNCHRONISATION. The indication of phase difference is the function carried out in generating stations by a synchroscope, or synchronism indicator, the most usual form of which has a rotating pointer actuated by the rotor of a small split-phase induction motor, with its rotor and stator supplied from the 110-volt secondary windings of the respective metering voltage transformers. It will be seen that a cathode ray oscillograph forms a simple alternative, one pair of plates being connected to the busbars, and the other to the incoming machine. The tube can be so mounted that a vertical line indicates exact synchronism.

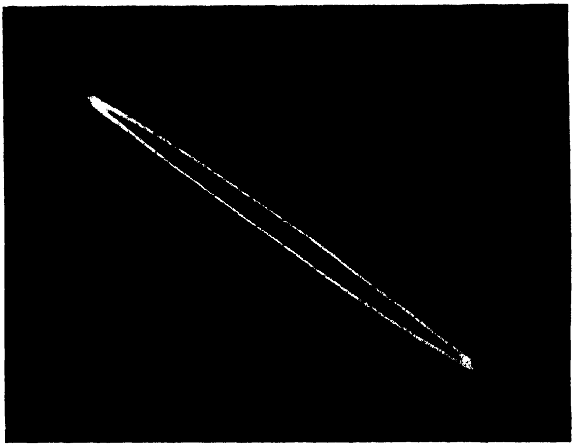

FIG. 66A.—Test on faulty induction motor

One important advantage of the latter arrangement is the absence of moving parts, while another is the smooth and exactly synchronised change in the indication. No amplifiers are ordinarily needed, and the scheme is a remarkably simple one. It does not, however, indicate whether an error is " fast " or " slow," and for many purposes therefore an addition is needed.

A directional scheme is shown in Fig. 67, in which the two voltage transformers are on the left, that leading from the busbars having duplicate secondary windings, each of which gives the full secondary voltage. These could form the usual metering transformers with the one unit modified as described, or they could be small " radio " type units connected in cascade with those for the meters. Then the secondaries of the two transformers are connected in series with each other, first with the " busbar " connections in one direction, and then, by means of the duplicate winding, with these reversed. One of the latter circuits is connected to the horizontal deflectors, and the other is passed through a phase-shifting circuit causing a lag of 90°, and is then connected to the vertical deflectors.

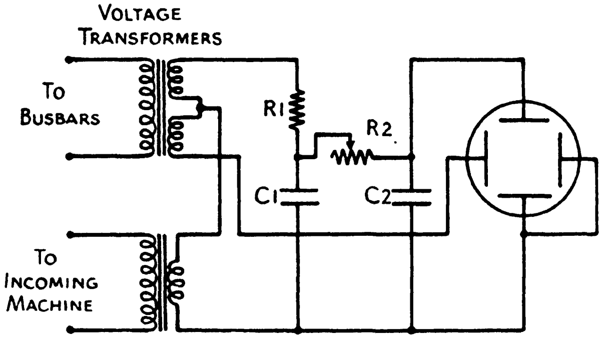

Fig. 67.—Directional synchroscope.

By this method of compounding the vectors from the two sources, the vertical line in the screen, representing exact synchronism, is caused to rotate just like the pointer of the mechanical synchroscope, and thus to show whether the incoming machine is fast or slow. In order to secure various angular positions of the line, it is necessary that the voltage applied to the two sets of deflectors shall be in phase, otherwise elliptical figures are produced. Reference to Fig. 68 will show that by compounding the vectors OA, OB, directly, and with OA reversed to OA′, two resultants at right angles, OX, OY, are obtained ; and by rotating OX through 90° to OX′ by means of the circuit $R_1C_1$ and the supplementary adjusting circuit $R_2C_2$, the resultants are brought into phase with each other, so that the luminous line takes up

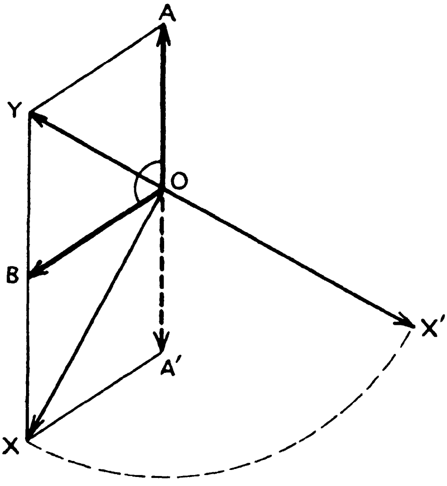

Fig. 68.—Vector diagram of directional synchroniser.

an angular position depending on the relative strengths of OX′ and OY.

For example, when the original currents, OA, OB, are just in phase with each other, OY = 2 OA and OX = O, with the result that the screen line is vertical; and when OA, OB are at 180°, the converse is true and the line is horizontal. If the construction be repeated for intermediate phase angles, it will be found that the line assumes an intermediate position corresponding to the degree of synchronism. Since the vertical line indicating exact synchronism extends over the full diameter of the screen, the latter need be only half the size of the usual synchroscope dial for equal visibility.

4. DIRECTION FINDING. The direction of a distant signal, which is usually an alternating discharge, is indicated by balancing against each other the strengths of the transmissions accepted by two frame aerials located with their vertical planes at right angles. For example, the north-south aerial might be connected through the necessary amplifiers to the "vertical" deflectors of the oscillograph, and the east-west frame through exactly similar amplifiers to the "horizontal" deflectors. Since the two components as received are in phase, a straight line is traced by the beam; but this is inclined at an angle representing their relative strengths, and hence indicating the exact direction of the transmitter relatively to the receiving aerials.

As in the last section, the simple scheme does not give complete information, in that the *sense* of the signal is not shown; *e.g.*, it might be coming either from, say, the north-east or the south-west. The deficiency is made good by means of a third, non-directional receiving aerial, which is used to modify the bias voltage of the cathode shield during alternate half-cycles, thereby rendering half of the indication indistinct or invisible. The phase relationship between the directional and non-directional waves is so adjusted that it is always the half of the trace directed away from the transmitter that is suppressed.* This is practicable since the directional waves are inverted when the sense is reversed.

One of the great advantages of the cathode ray method of indicating direction is the complete absence of time-lag, the instrument providing its indication instantaneously by "direct reading."

5. DISTORTION DETECTION. Faithful reproduction in an acoustical apparatus, such as a wireless set or radio-gramophone, depends on the output from each stage corresponding exactly with the input, no new frequencies being added, and no existing frequencies increased, reduced,

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* See Watt, Herd, and Bainbridge-Bell, *The Cathode Ray Oscillograph in Radio Research* (H M. Stationery Office), Part 4.

or altered in phase relatively to the others. A phase alteration will be detected as described in sections (1) and (2), by the figure in the screen becoming an ellipse instead of a diagonal ; while a change in volume of any part of the input will be shown by the diagonal line bending over or departing in some other way from straightness.

The circuit employed for such tests is shown in Fig. 69, and is quite a simple one. An amplifier is supposed to be under examination, and the potentiometer R will be adjusted to compensate for the gain and make the deflections brought about by the two pairs of plates approximately equal. Typical results are illustrated in Fig. 70, where the four oscillograms respectively indicate zero distortion, slight and serious distortion at the ends due to overloading, and phase displacement. Tests would be made over the whole frequency range by appropriately varying the wave produced by the oscillator.*

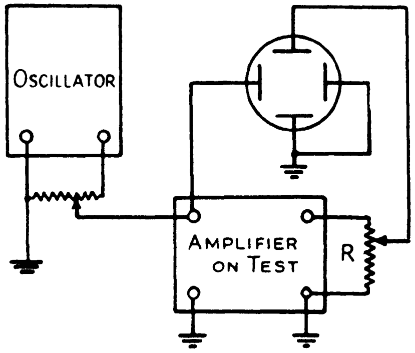

FIG. 69.—Scheme for distortion test on amplifier.

6. FREQUENCY COMPARISON. The maintenance of an exact frequency is a matter of the greatest importance in connection with wireless transmission, as is evidenced by the extreme accuracy of the methods employed to maintain a constant standard. Two methods are in regular use, viz., a 50 kc/s, quartz crystal, and a 1 kc/s electrically maintained tuning fork. The former consists of a thin plate cut from a single crystal in a definite manner and to an exact size, having the property of vibrating at the standard frequency to within a few parts in a million, provided its temperature is kept to within 0·1° C. of a specified value. It is therefore housed in a constant temperature oven. The tuning fork is capable of about the same accuracy, if its temperature is maintained constant to within 0·005° C., and the atmospheric pressure is kept within prescribed limits. The oven employed is a double one, *i.e.*, an oven within an oven, both thermostatically controlled.

The measurement of phase differences described in the previous section was in effect a comparison of frequencies by the formation of Lissajous' figures for a 1 : 1 frequency ratio. Other ratios can be compared by the interpretation of more complicated figures, produced by means of exactly the same scheme of connections. In order to obtain a satisfactory datum, one of the frequencies employed should be a calibrated standard, and one of them also should be capable of variation at will.

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* See Appendix C.

If the frequencies to be compared are approximately equal, the resultant figure will pass through the various transitions shown in Fig. 65 in turn, the rate at which the change takes place being a measure of the difference between the two. For example, if the whole cycle from the right-handed diagonal back again to the same figure is passed through once per second, then there is a difference of just 1 cycle per

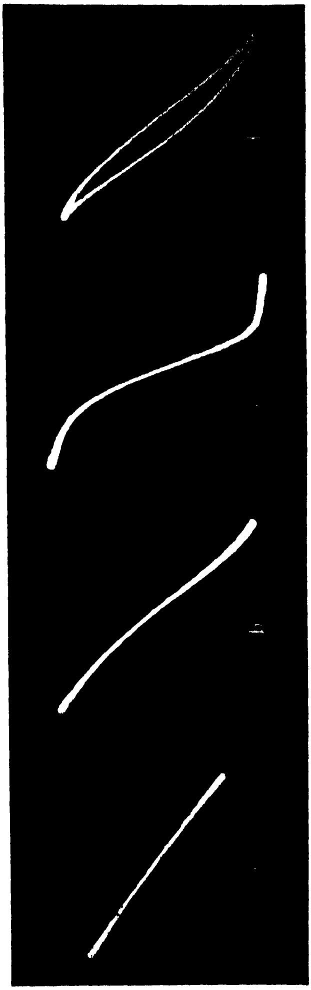

FIG. 70.—Distortion test on amplifier. (a) No distortion. (b) Slight overload. (c) Serious overload. (d) Slight overload and phase displacement.

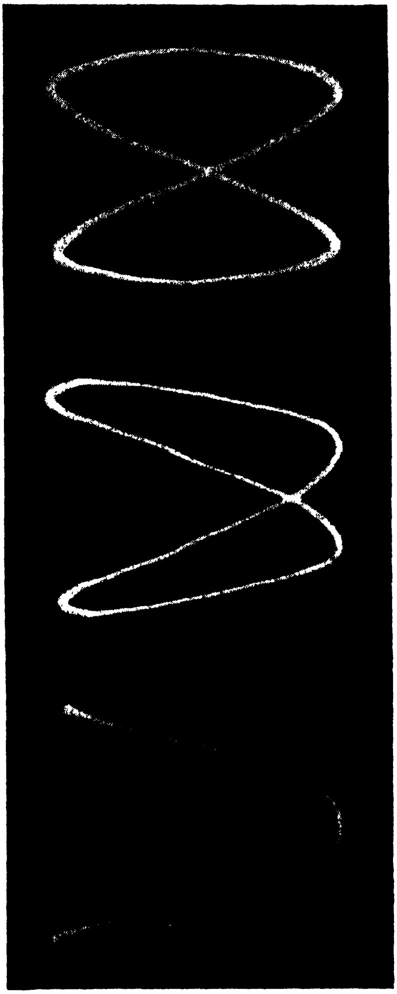

FIG. 71.—Three Lissajous' figures corresponding to a frequency ratio of 2 : 1. That on the right gives the most reliable indication. The components were not pure sine waves.

second between the frequencies. Comparison is easiest, however, if the figure be held stationary by adjustment of one or the other, and either of the limiting shapes, viz., the diagonal line or the circle, may be regarded as indicating a 1 : 1 ratio.

FIG. 72.—Figure from two generators giving 200 c/s square wave and 50 c/s respectively.

If the ratio be 2 : 1, the limiting figures are as shown by the two outside oscillograms in Fig. 71, viz., either a U shape or a figure 8 ; and similarly 3 : 1 and 4 : 1 are indicated by either N and M shaped figures, or figures with 3 and 4 loops respectively. Of the two types of figure, the latter is the more convenient, as it is not so much altered by a slight difference in phase as the other, and also on account of the simplicity of counting the number of loops in either a horizontal or vertical direction. Ratios of any number to 1 will thus be seen to present little difficulty.

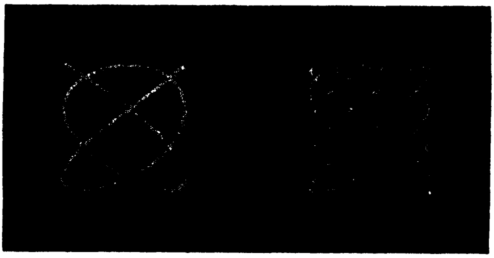

FIG. 73.—Figures indicating a 5 : 4 ratio, that on the right being the more useful.

A 4 : 1 ratio is however shown in Fig. 72, in which the former type of figure is used. This oscillogram is of interest for several reasons. In the first place, the higher frequency generator was specially designed to give a " square " wave, actually shown in Fig. 81 later. Secondly, the test was taken to check the phase relationship of the two machines, which were required to be accurately coupled, with their respective voltage vectors at a particular angle to each other.

Intermediate values such as 3 : 2, 5 : 2, and 7 : 5, in which neither number is unity, give somewhat more complicated designs, as shown in Fig. 73, in which the ratio is 5 : 4. If the limiting " full-faced " figures be obtained, corresponding with the circle for the 1 : 1 ratio, they will be seen to follow quite a simple rule. This is that the ratio is made up of the number of loops counted along one side of the figure, and the number along a side at right angles. The examples in Fig. 73 are numbered in order to make the principle clear. The left-hand figure is in reality an " edge-wise " version of the other, the apparent dead-end marked 1 being an " edge " view of the loop 1 on the right. Similarly the loop 2 (3) consists of the right-hand loops 2 and 3 superposed, and so on.

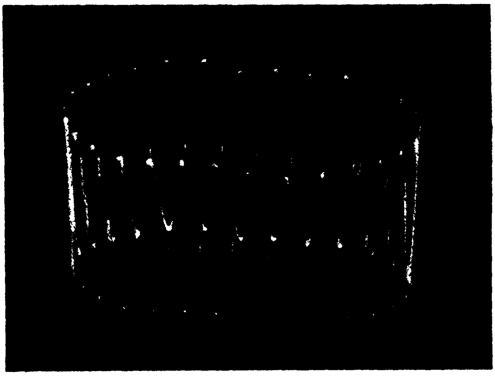

FIG. 74.—Elliptical figure representing a 29 : 2 ratio.

It will be evident that although these latter figures can be easily interpreted when the number of loops is relatively low, and especially when the component curves are accurate sine waves, increasing difficulty is experienced when the numbers approach double figures. For ratios involving numbers in excess of about 10 it is an advantage to spread the figures out in order to facilitate counting. Now the spot, in tracing out these closed figures, moves repeatedly across the screen and back again, and a " phase-splitting " coupling can be introduced between the two deflector circuits which will lower the portion moving from, say, left to right and correspondingly raise that going from right to left. The figure then has a ring-shaped appearance, with front and back portions which can be readily distinguished from each other and their loops counted.

The modified scheme has already been shown in Fig. 31, from which the addition will be seen to consist of a resistance R and a condenser C connected between the two main circuits in such a way that the low-frequency sweep is transformed from a straight line to an ellipse or circle. An oscillogram exemplifying the advantage of the method is shown in Fig. 74, indicating a ratio of 29 : 2. The estimation is carried out by counting the loops or peaks round the top of the band (29) for one term, and the number of interlacing rings (2) for the other. A simpler figure forming Fig. 32 shows a ratio of 15 : 1.

7. CONDENSER POWER FACTOR. The power factor of condensers can be compared by connecting a standard unit and the unit under test so that the voltages across their terminals due to an oscillator applied to the two in series produce vertical and horizontal deflections respectively. Then a diagonal straight line figure would indicate that the power factors are equal, and difference in phase angle can be estimated as described earlier.

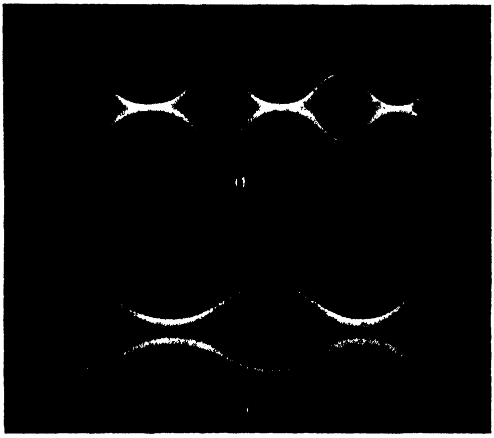

FIG. 75.—Two modulated carrier waves. The upper (a) shows a carrier of normal frequency ; while the lower (b) carrier was of specially low frequency (4 kc/s) to illustrate the principle.

8. MODULATION. Modulation in radio transmissions may be described as the superposition of an audio-frequency voltage upon one of much higher frequency, in such a way that the amplitude of the " carrier " wave is caused to vary symmetrically on either side of the neutral axis. It will be evident that this process, which is exemplified in Fig. 75, can only be carried out completely when the total amplitude of the audio-wave above and below its own neutral axis does not exceed the total amplitude of the carrier ; but that values in excess of this will give rise to zero amplitudes of the modulated wave after the axis

has been reached, when they should continue to decrease. Over-modulation is thus one of the chief causes of distortion.

Two examples of modulated waves are shown in the figure. That on top (*a*) is a carrier wave of a usual radio frequency, while below (*b*) is a wave of especially low frequency and less completely modulated. Both audio-frequency modulating waves are good sine curves, the chief difference between the two illustrations being that in (*a*) the high radio-frequency has produced a " solid " figure without any sign of alternation, while in (*b*) the texture due to the separate alternations is visible. Both were taken with the aid of the usual linear time-base, synchronised with the audio-frequency wave. The composition of the modulated wave is indicated by the sketch forming Fig. 78 (a). Distortion can be detected by examining the shape of the wave ; for example, over-modulation would be shown by the individual cycles being separated from one another by short thick lines along the axis.

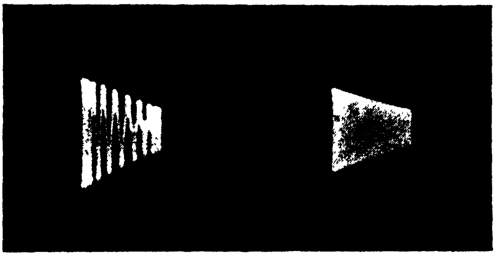

FIG. 76.—Two trapezoidal figures showing no distortion.

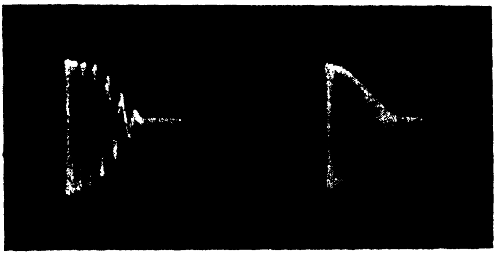

FIG. 77.—Two trapezoidal figures showing over-modulation, frequency as in Figs. 75 and 76.

More information can, however, be obtained by proceeding along the same lines as the previous sections in this chapter, viz., by connecting the input (audio-frequency wave) to the horizontal plates and the output (modulated carrier) to the other pair. In the present case, instead of a single diagonal when there is no distortion as in Fig. 65, it is evident that there will be two diagonals sloping in opposite directions, one corresponding to the upper and the other to the lower part of the envelope. At the one end there will be a vertical line representing the widest part of the modulated wave, and at the other, one representing the narrowest part. Thus a trapezoidal figure will be produced, as shown in Fig. 76 (right) for the usual radio frequencies, but more clearly in Fig. 76 (left) by means of the low-frequency carrier.

Over-modulation produces " pinched-out " figures as in Fig. 77. An inspection of that with the L.F. carrier reveals an interesting fact, namely, that the figure consists of " going " and " return " waves superposed on each other under normal conditions, that is, when the audio-voltage is in phase with the modulated carrier. When they are not in phase, the two waves separate, giving a distorted figure as in Fig. 78 (m), which was actually obtained by deriving the audio-voltage from some other point in the pre-amplifier than the output of the modulator.

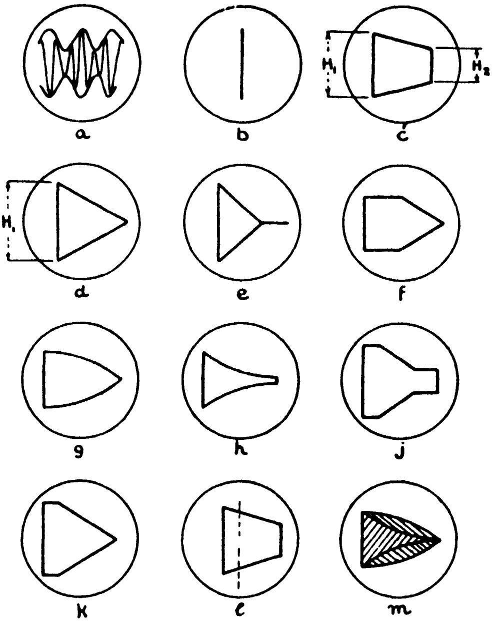

FIG. 78.—Trapezoidal figures produced by defective modulation.

The effects of various errors are illustrated in Fig. 78. Here (b) shows the vertical line traced before connecting the audio-voltage, and (c), the normal trapezoid, indicating a modulation of 100 × $(H_1 - H_2)/(H_1 + H_2)$ per cent. In the triangular figure (d), the modulation is exactly 100 per cent., $H_2$, being zero ; and any more will cause distortion as in (e), which may be compared with Fig. 64.

In (f) the R.F. grid output is insufficient, the positive A.F. peaks being cut off because the R.F. amplifier cannot provide an output proportional to the peak modulating voltage. The non-linear figure (g) will more probably be due to insufficient excitation of the Class C stage clipping the peaks of the modulated wave. Opposite curvature as in (h) indicates a regenerative Class C. R.F. amplifier ; while (j) is characteristic of a screen-grid R.F. amplifier, the anode of which is modulated but the screen operated at a fixed voltage. In (k) a screen-grid R.F. amplifier has its screen alone modulated, and consequently the output cannot increase to 100 per cent. modulation ; while in (l) the pattern has moved towards one side of the carrier line owing to an asymmetrical audio-wave, the negative A.F. peaks in this case being greater than the positive and causing the trapezoid to expand more to the right than the left.

## CHAPTER SEVEN

# APPLICATIONS REQUIRING A REPEATING TIME BASE

The very numerous class of test will now be described in which the cathode oscillograph is made to trace curves recording the variation of any appropriate quantity with time ; and the present chapter will be devoted to those simpler cases (as far as ease of observation and photography are concerned) in which the test is repeated cyclically for as long as is desired by the experimenter.

Reference has already been made to the wide variety of time bases available for the cathode ray oscillograph. Of these, the rotating drum and the cinema type of film are the two principal methods employed for the electromagnetic oscillograph, and their use for the cathode instrument is on similar lines. Both, of course, give a linear time scale, which enables the exact shape of the wave to be recorded. The same is true of the traverse depending on the charge or discharge of a condenser through a saturated diode or a suitably biassed pentode, while the ideal is nearly attained by deflecting with the portion of a sine-wave voltage near the axis. Of these, the condenser method enables a recurrent or cyclic phenomenon to be imposed repeatedly upon the same trace on the fluorescent screen in order to facilitate visual study or photography.

It is, however, frequently unnecessary that the exact wave-shape shall be shown, as regards its spacing on the time scale. When the object of the test is the detection of peaks or ripples, a simpler base circuit is sufficient. In this connection it will be recalled that the remaining time-base used with the electromagnetic instrument, namely that using the falling-plate, does not give an accurately linear result ; yet it is still a favourite method for photographing wave-forms.

A more common requirement is the magnitude of the voltage at various intervals, and this can be fully met by superposing on the non-linear record a " timing " wave, obtained by energising the spot by means of an oscillator after the main record has been taken. Examples of this practice are given in Figs. 105 and 110.

Details of the various time-bases were provided in Chapter III, and also in connection with some of the oscillographs described in Chapter IV. The process of synchronising the base with the " work," and the method of time-marking, were also included in Chapter III.

The principle of superposing repeated images upon one another is utilised in two ways, which will now be treated separately. Part I is devoted to the recording of cyclic phenomena, and Part II to the similar treatment of surge phenomena, small scale reproductions of which are caused to recur a sufficient number of times for convenient observation and photography.

## PART I

## Recording of Cyclic Phenomena

1. ROTATING MACHINES. The most obvious examples of cyclic or recurrent phenomena are the wave-forms of rotating machines. Alternating current equipment is tested in this way in order to detect any departures from the true sine wave ; but D.C. plant is also subject to cyclic irregularities, which are detrimental for certain classes of machine. The record shown in Fig. 79, for example, is typical of tests made upon D.C. generators of 20 to 30 kW, manufactured for telephone systems. There are two sets of ripples visible in the oscillogram, that with the lower frequency, four cycles of which are present in the figure, being due to the armature slots ; while the commutator bars are responsible for the superposed high-frequency alternation. Limits are fixed for such departures from linearity by specification, and the cathode oscillograph affords a highly convenient means for measuring them.

FIG. 79.—Voltage wave of D.C. generator.

As far as the test-room is concerned, a visual indication is usually all that is necessary, and the great convenience of the fluorescent screen then gives it a big advantage. Photographic records are required at times by the design office or by inspectors, and in some cases might be made with equal or even greater facility by means of an electromagnetic instrument ; but for the present purposes the cathode ray offers further advantages. The first is at once apparent, namely the suppression of the main D.C. component, which is stopped by the coupling condenser in the amplifier. Further, the advantages of high magnification and easy positioning are evident in this example.

It should be noted that the oscillograms forming Fig. 79 as well as Fig. 80 have been photographed with the graduated screen in position ;

and the square divisions may be made out as thin interruptions of the record.

FIG. 80.—Alternator wave, showing slight asymmetry.

Alternating current generators of all sizes, up to the largest turbo-alternators, are tested for wave-distortion, which can take the form of slot-ripple, harmonics due to approaching saturation of the core, and certain other aberrations. The oscillogram in Fig. 80 is a close approximation to a sine wave, but gives evidence of slight asymmetry, probably due to a very small second harmonic.

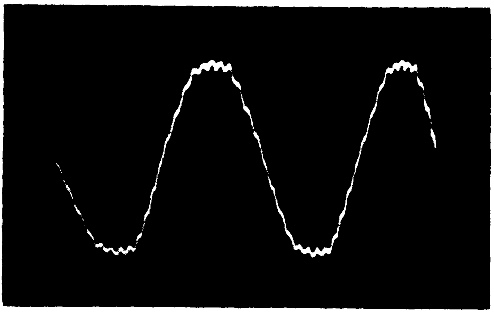

FIG. 81.—Alternator wave, showing 1,200 c.p.s. ripple.

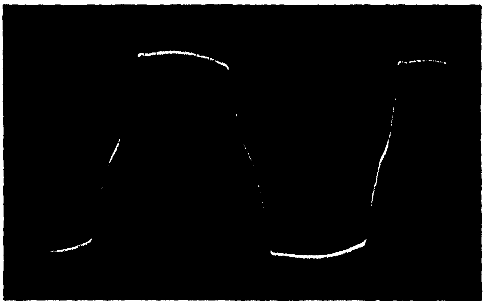

FIG. 82.—" Square " alternator wave.

There is a well-marked ripple in Fig. 81, which was taken from a 45-kVA machine. As the ripple frequency is 1,200 c.p.s., it is getting beyond the compass of the electromagnetic oscillograph. In this particular instance the characteristic was first taken by means of the latter, but the ripple in question was so nearly invisible that it escaped notice until the cathode oscillogram revealed the true state of things. It is probable that such higher frequencies frequently exist without detection when reliance is placed solely on the electromagnetic instrument. An oscillogram from an alternator designed to give a " square " wave is shown in Fig. 82.

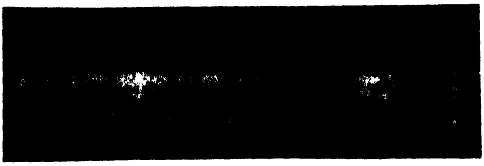

FIG. 83.—Fault-finder figure showing a short-circuit on the right and a partial short-circuit on the left.

A more elaborate method is used for testing D.C. generators and motors, in order to detect winding errors in the armature, such as reversed coils, coils with too many or too few turns, open-circuited coils, short-circuited sections, or earths ; and to locate the faulty section.

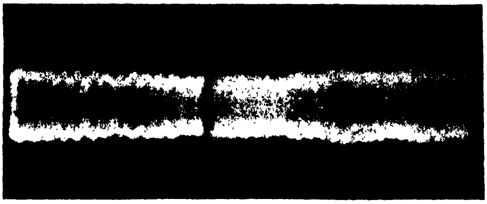

FIG. 84.—Fault-finder figure showing open circuit.

The armatures under test are mounted one at a time on a bedplate, where they are rotated at about their normal running speed by a motor. Two pairs of brushes are then lowered to the commutator, of which one pair are 180 (electrical) degrees apart and act as feeding points. The other pair are arranged to bear upon adjacent or next-to-adjacent sectors. These brushes are connected to the vertical deflectors of the oscillograph. There is a third pair of brushes that are short-circuited together once every revolution by a contact on the shaft, and trigger the time base. These can be rotated bodily round the shaft so as to occupy any desired position.

When therefore all the windings are sound, a series of parallel and equal ordinates are shown upon the oscillograph screen. But if any of the sections is faulty, its ordinate is of different height from the others. Two examples are given in Figs. 83 and 84 respectively. A dead short-circuited coil will have no voltage across it, and its ordinate will therefore have zero height. A fault of this description is seen on the right of Fig. 83, while there is also a partial short-circuit on the left. Since the brushes cannot be so narrow as to touch only one segment at a time, the ordinates immediately adjacent to the faulty one are also partly affected. An " earth " in a winding would be shown by a gradual reduction in the height of the neighbouring ordinates down to the axis.

An open-circuited section would have all the voltage drop applied to its ends, indicated by a sudden peak, as in Fig. 84.

To locate the faulty section, the triggering brushes are rotated until the abnormal ordinate comes at the end of the figure. The motor is then stopped and the armature is turned by hand until the time-base trigger contacts are joined together, when the pick-up brushes are bridging the defective coil.

Direct current may be used for energising the winding, but A.C. at a fairly high frequency has the advantage of breaking down faults with greater certainty, and a value of about 3,500 c/s was used for the tests illustrated. It is for this reason that there are two or more ordinates per sector, rendering the outlines of the record somewhat blurred.

All the faults mentioned except reversed coils are shown up by placing the exploring brushes on adjacent sectors. To detect reversals, the brushes will need to be two sector-widths apart, when the faulty coil will give a null deflection with each of its sound neighbours.

The above scheme has been recently extended * by L. G. Ward to the finding and recognition of faults in squirrel-cage rotors, and in other rotors and stators. These present a rather more difficult problem than the D.C. armature, which enables contact to be readily made with each coil of the winding ; and some substitute for the commutator and brushes is now required. The rest of the apparatus, consisting of the bedplate, chuck, means for rotating the moving part, and time-base with adjustable trigger point, are retained as before.

An electro-magnet excited from a D.C. source is so arranged that its flux becomes interlinked with the individual windings as they pass in succession before its poles. For example, the poles may be brought very close to adjacent teeth of the core ; or in the case of a consequent pole stator, one wound pole and the adjacent consequent pole would be nearly bridged by the magnet. Then a momentary voltage and

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* Prov. Pat.

circulating current would be generated in each winding, which would induce a proportionate secondary or " reflected " voltage in the magnet coil. The Y-plates of the oscillograph are connected across the latter.

Now it is obvious that the current induced in the sections of the winding will be directly affected by their impedance, which in turn is affected by any fault they may possess ; and the result will be a sequence of vertical lines resembling those in the D.C. case shown in Figs. 83 and 84, and giving analogous indications. Among the faults that are definitely revealed are broken joints, high resistance joints such as those due to bad soldering, and also all the possible faults in a wound rotor or stator, including earthed winding, short-circuited turns, magnetically-bridged coils, and broken shading rings.

2. TRANSFORMERS. For transformer testing also the oscillograph is used to measure the magnitude of the harmonics. During recent years, economy in first cost has been increasingly effected by working at higher flux densities. This has, however, entailed an increased hysteresis loss, associated with distortion of the sine wave. The effect of the latter is the production of odd harmonics, of which the 3rd, 5th, and 7th are the most important. In order to check the tendency, the amounts of these that may be present are restricted by specification, and are most conveniently recorded by the cathode instrument. Some test-rooms carry out the measurement as a matter of routine. An example is shown in Fig. 85, which was recorded on the primary side of a 45,000-kVA, 33/132-kV delta/star transformer while running on open circuit, and therefore while the flow consisted almost entirely of magnetising current. As the 3rd harmonic was removed by the delta winding, the 5th predominates, and gives the curve its characteristic shape.

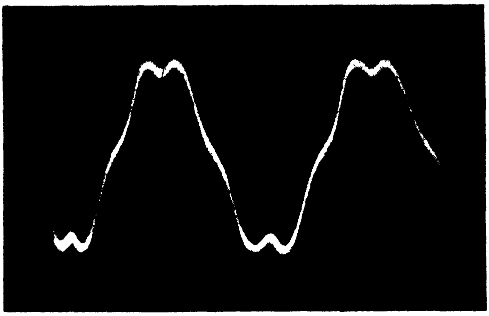

FIG. 85.—Open circuit transformer wave, with form factor 1·12.

3. MERCURY ARC RECTIFIERS. The mercury arc rectifier probably depends more upon the cathode oscillograph during its manufacture than any other major piece of electrical equipment. First, the instru-

ment is used for the examination of wave-form, both for general test purposes and for determining the cause of anomalous behaviour. Secondly, it affords a reliable method of measuring the arc-voltage and arc losses. Thirdly, it is employed after installation for locating the origin of high-frequency disturbances and determining the extent of their influence. Finally, it forms a very convenient indicator for securing correct phasing when connecting up grid-control equipment.

A typical oscillogram of the D.C. output from a six-phase rectifier is shown in curve (*a*) in Fig. 86. This will be recognised as a composite wave formed by the tops of a succession of sine loops, the neutral axis of which would be some considerable distance below the figure. Such a voltage is sufficiently steady for most purposes, and would ordinarily be used without any alteration ; but there are special situations where a smoother supply is necessary, and the need is met by employing filters to remove enough of the high frequency components to fulfil the requirements.

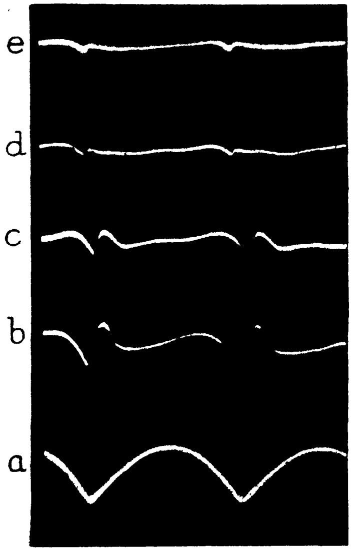

FIG. 86.—Voltage waves from six-phase rectifier.

Now the harmonics present in the D.C. output are the 6th, 12th, 18th, 24th . . . , and each of these can be by-passed by means of an acceptor circuit composed of a capacity and an inductance in series, tuned to the particular wave-length that it is intended to remove. Thus a rectifier may be shunted by a series of four or five such wave-traps in parallel. The remaining waves in the figure show the effect of eliminating the above harmonics in successive stages, viz., (b) 6th, (c) 6th and 12th, (d) 6th, 12th, and 18th, and (e) 6th, 12th, 18th, and 24th. Again, the convenience of the cathode oscillograph for this kind of work will be seen, and especially the ability, afforded by the amplifier, to cut out the D.C. component and pass only the fluctuating part of the voltage through the tube itself.

The curves illustrated are characteristic of mercury arc rectifiers in general, and departures from this shape would almost certainly be due to the circuit and not to the rectifier. Most wave-form tests would therefore require to be made on site, and not in the factory, and the portability of the cathode instrument assists towards this end.

Measurement of the arc voltage of a rectifier is ordinarily not an easy matter, largely because its value of only 18 to 30 volts is very low in comparison with the peak value of the load voltage, which somewhat exceeds twice the D.C. output voltage and would also have to be carried if other types of instrument were used. With the cathode oscillograph, a neon tube, or some kind of rectifier, is used to remove the negative half-cycle, thus leaving only the arc voltage to be dealt with. A typical example is shown in Fig. 87, in which the first peak is the point at which the arc strikes, and the subsequent amplitude depends upon the load.

Arc losses are measured by integrating successive products of the arc volts and amperes. Four oscillograph records are taken in quick succession upon the one film by means of four sensitive relays, *e.g.*, of the " telephone " type, giving the voltage and current waves and two calibration spots. An example is given in Fig. 88, which it should be noted was taken at extreme overload, and the voltage wave, occupying the upper position, hence shows considerable modification as compared with that in the last figure. The " firing " peak on the left is now not half the total height ; the slight vagueness at maximum voltage is in all probability due to the action of one of the relays. The current wave shows signs of saturation in the interphase transformer due to the high overload.

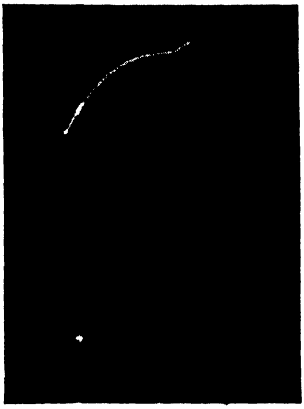

FIG. 87.—Arc voltage of mercury arc rectifier.

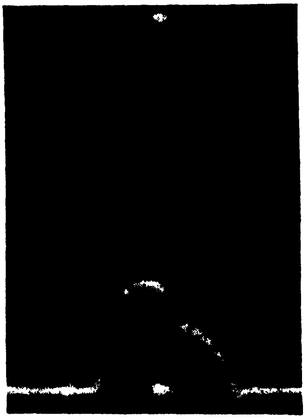

FIG. 88.—Arc losses in mercury rectifier.

A typically good current wave is indicated in Fig. 89. The crest portion of the wave shows no signs of saturation ; while the inclined portions in the front and rear, the slopes of which depend upon the load reactance, enable the total circuit reactance to be estimated, the load being known.

An important requirement in the testing of mercury arc rectifiers is to confirm that the voltage is evenly shared in the two half-windings of the inter-phase transformer groups. The D.C. load current passes through the two parts of the winding in opposite directions, and it therefore develops a voltage consisting of the difference between that of the two groups. If the super-imposed loops of the rectified polyphase voltage be considered, it will be seen that the difference voltage consists of the kite-shaped areas of overlap, giving a very peaky triangular wave of triple frequency, an example from an actual test being shown in Fig. 90. The symmetrical shape indicates that the voltage is evenly divided.

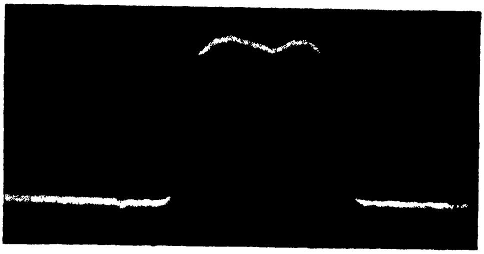

FIG. 89.—Current wave of mercury arc rectifier.

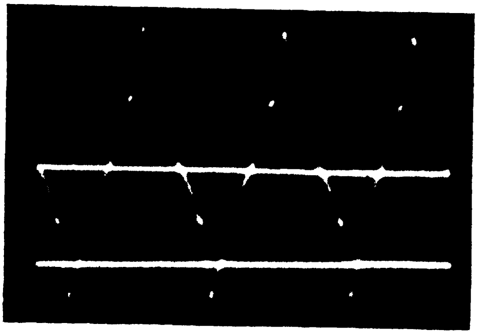

FIG. 90.—Voltage across inter-phase transformer of six-phase mercury arc rectifier.

The input voltage and current waves into a rectifier are shown in Fig. 91. These were taken with a double-beam oscillograph, shown in Figs. 9 and 43, and further dealt with on p. 114. Since the changes in the current are to a large extent the cause of the peculiarities in the voltage wave, it is a great advantage to have them exactly correlated in time as in the figure. For example, there are six small dips regularly spaced round the voltage cycle, appearing in four cases like interruptions, which are due to momentary short-circuits between adjacent anodes at the instant of change-over of the arc ; the dips near the axis being caused by the current in the wave recorded, and the rest by that in the other phases. The similarity of the current wave to the anode current in Fig. 89 should be noted.

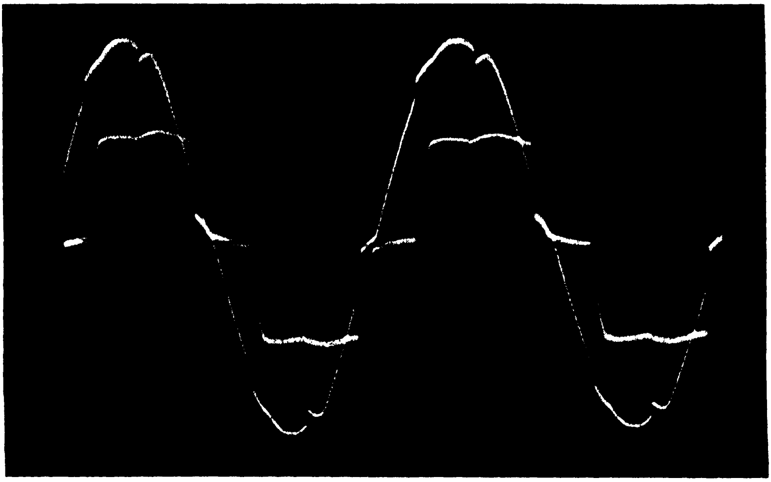

Fig. 91.—Voltage (outer curve) and current input into mercury arc rectifier.

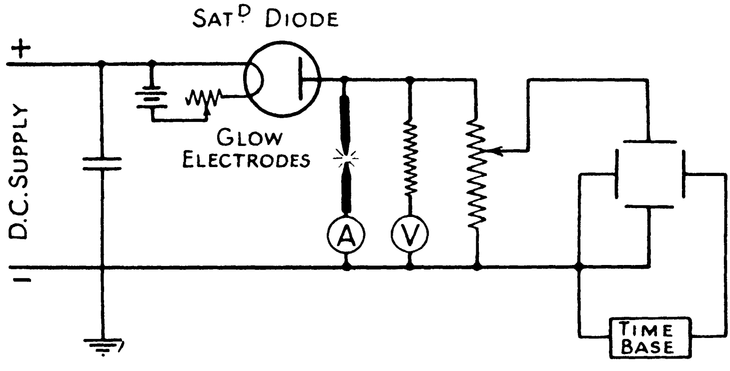

Fig. 92.—Glow discharge anemometer.

4. AIR VELOCITY. Most readers will be familiar with several different types of anemometer. Nearly all are in effect small windmills, differing among themselves with regard to the manner in which the shaft velocity

is recorded, though some are based on more static principles ; but with one exception all possess the serious defect that they are quite incapable of detecting speed variations having a period of less than several seconds. This performance is no doubt sufficiently precise for observations upon the weather, or for measurements in mine ventilation ; but in modern aerodynamic research, the effect of turbulence is of the greatest importance, and demands the ability to detect and record accurately speed fluctuations having a frequency of hundreds of cycles per second.

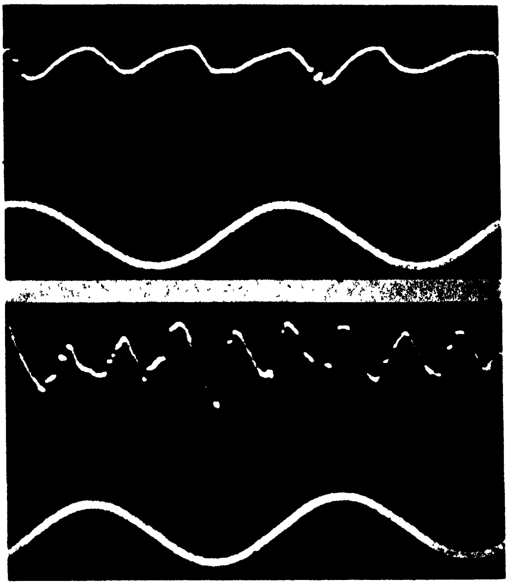

Fig. 93.—Turbulent pressure waves due to air velocities of 9·9 m/s (upper wave), and 16·3 m/s (lower wave). Timing waves—50 c/s.

The exception mentioned above is the hot-wire anemometer, which depends on the differential cooling of the wire by air currents of different speeds, with a consequent variation in resistance. Its readings are, however, affected by thermal time-lag, and its sensitivity varies seriously with turbulent frequency.

These defects are avoided by means of the detector designed by Professor Lindvall,* the arrangement of which is shown in Fig. 92. It is based on the effect of air velocity upon the voltage drop in a minute glow discharge, due to a constant current of from 10 to 30 mA at a total voltage of 400, passing between pointed electrodes 1·5 mm. in diameter, separated by a gap of from 0·1 to 0·25 mm. The points are of platinum or tungsten, and have a taper of 20°.

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* See *A Glow Discharge Anemometer,* Trans. A.I.E.E., Vol. 53, July, 1934, p. 1068.

As shown in the figure, a smoothed D.C. supply discharges across the gap through a saturated diode, which keeps the current constant at the desired value. Adjustment of the latter is carried out by means of the filament rheostat, giving a range of from 0 to 50 mA. The voltage drop across the gap is taken to the vertical deflectors of the oscillograph, a time-base being connected to the horizontal plates. Calibration is effected by switching a 45-volt battery in series with the glow voltage.

Typical oscillograms are shown in Fig. 93, which were taken during a test of the variation of turbulence behind a cylindrical obstacle with air velocity. The upper record gives a turbulent frequency of 133 c/s for a velocity of 9·9 m/s, which increase to 220 c/s and 16·3 m/s respectively in the lower figure. The results conformed exactly with the laws previously formulated, and with observations made by other means. No time-lag has hitherto been observable, and a nearly flat frequency response characteristic has been found to assist calibration considerably.

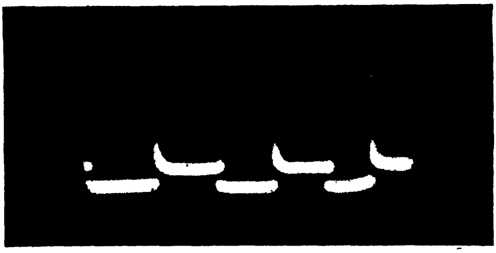

FIG. 94.—Transient at contacts of electric bell.

5. SHORT OPERATIONS. The need is frequently experienced for a method of measuring extremely short intervals, such as the time of operation of a small relay ; and, in addition, the behaviour of the current or voltage during such an operation often has to be ascertained. Both purposes can readily be achieved by means of a cathode ray oscillograph. The proportion of the whole period that is occupied by the movement of the contact or by any other part of the cycle is at once made evident, while a knowledge of the time-base frequency completes the information required. The shape of the voltage (or current) wave will supply details as to the performance. The example in Fig. 94 shows the voltage fluctuations across the contacts of an electric bell, and affords a typical record of the transients during the breaking of a circuit.

6. TIMEPIECES. A sensitive and convenient method is afforded by the oscillograph for checking the time-keeping of clocks and watches against a standard, the only proviso being that the two that are being compared must be designed to give the same number of ticks per second. The sound is picked up from both by means of microphones, and the resultant impulses from the standard are used to " trigger " the time base. If then the impulse generated by the test clock, and taken to the vertical deflectors, is exactly in synchronism with the standard, its image on the fluorescent screen will be stationary ; but fast or slow running will be indicated by a gradual drift in one direction or the other.

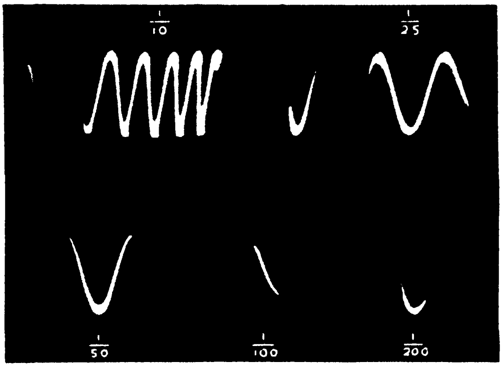

FIG. 95.—Test of Compur shutter with 50 c/s wave.

7. SYNCHROSCOPE. A synchroscope for paralleling alternators, which will indicate whether the incoming machine is fast or slow, can be arranged on the above principle, if the leads from the busbar and incoming generator panels be respectively substituted for the leads from the microphones. The two will be in phase when the positive peak of the wave coincides with the vertical diameter of the screen ; and the direction of drift will indicate whether the new machine is fast or slow.

8. SHUTTER SPEEDS. The checking of shutter speeds in connection with photographic cameras has been carried out by Mr. J. S. Forrest * by means of a sealed-off tube with a screen having no afterglow (*e.g.*, a Cossor " J " Type). Advantage is taken of the high accuracy of the 50-cycle power-supply frequency, about 2 to 6 cycles of which are recorded upon the oscillograph screen. Photographs, similar to those shown in Fig. 95, are taken of the screen through the shutter under test, and the length of the trace upon the film affords a measure of the time

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* See *Miniature Camera World*, Vol. V, No. 5, April, 1941.

that the shutter is open. For example, a complete half-cycle loop represents $\frac{1}{100}$ sec., and fractions of a loop are easily scaled off.

The exposures are made at full lens aperture upon a moderately fast film, and it was found that a peak-to-peak amplitude of 0·1 in. is sufficient to enable accurate measurements to be made. Thus a considerable number of " shots " can be taken upon the one film if the camera is mounted on a tripod or other definite support. Lack of sluggishness in opening and closing is evidenced by crispness at the beginning and end of the trace.

It will be observed that the first two records in Fig. 95 are divided, the shutter opening in each case somewhere near the middle of the wave, remaining open during the (invisible) fly-back, and closing during the first loop. The first four speeds are recorded as exact, and the $\frac{1}{200}$ sec. operation is actually about 0·007 sec.

**Use of Circular Time Base.** Instead of the linear sine-wave as described above, a circular time base may be employed to advantage for many time measurements. By means of the split-phase circuit shown in Fig. 31 of Chapter III, the alternating voltage is applied to both pairs of plates in quadrature, with the result that the spot is caused to rotate in a circular orbit at the rate of once per cycle. As the applied frequency can be regulated to a very high degree of exactness, the arrangement possesses the characteristic of an accurate and fine-reading time-piece.

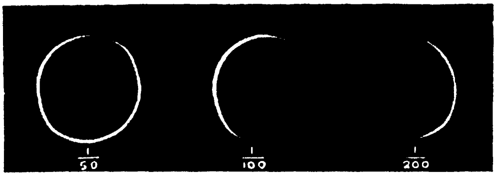

Fig. 96.—Test of Compur shutter by circular time base. The angles, 180° and 117° show the periods in the two faster tests during which the shutter was fully open.

If, for example, the 50-cycle mains voltage is used for the time base, then a complete revolution of the spot, or 360°, represents 0·02 sec., *i.e.*, 1 milli-second per 18°. By deriving the voltage from an oscillator, a calibrated frequency of 1,000 c/s or more can be obtained, enabling much smaller time intervals to be measured. The chief precautions are to make the ohmic value of the resistance R equal to that of the reactance due to the capacity C (*i.e.*, $1/(2\pi fC)$ ) at the applied frequency f ; and to use a high-quality condenser for C with negligible leakage and therefore very low power factor. A good paper condenser should be satisfactory.

8A. SHUTTER SPEEDS—(*contd.*). Then the testing of camera shutters would be carried out as before, by photographing the rotating spot and measuring the angle subtended by the arc traced on the screen, as shown in Fig. 96. Again a screen with negligible after-glow is necessary. The 50 c/s frequency used will not measure intervals exceeding 0·02 sec.; but the three tests that were possible confirmed the previous results quite closely.

9. RELAY OR SWITCH TIMING. Timing of a relay or switch operation can be effected by connecting the contacts in parallel with the resistance R of the split-phase circuit, so that the resistance is short-circuited while the contacts are closed. The spot will leave the circle under these conditions and move in a horizontal straight line after the manner of an ordinary time base; the paths from the one to the other being executed so rapidly as to be almost or quite invisible. An afterglow is permissible and even advantageous for this kind of test. An example is shown in Fig. 97, in which a pair of contacts are closed for 40° out of the total 360°, *i.e.*, for 1/50 × 40/360 sec., or ·0022 sec.

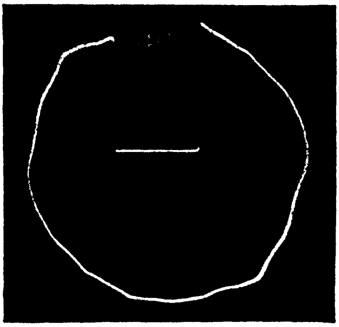

FIG. 97.—Test on relay operation.

10. MECHANICAL OPERATIONS. Mechanical operations can be timed by attaching light contacts to the moving part, which can carry out the above connection and disconnection.

11. DELAY IN TELEGRAPH CIRCUITS. An interesting application of the circular time base occurs in the testing of telegraph relays. Successful telegraphy, especially of the modern high-speed type, depends upon the relays maintaining a constant delay for all signals; otherwise the waves as received will differ more or less widely from their transmitted form. The whole telegraph circuit is actually involved in this condition, including the apparatus at the near and distant ends, and the channel connecting them, whether the latter consists of a line or carrier-current transmission. It is becoming the practice to subject every installation to a routine test before leaving the works, followed by periodic tests in its after-career, in order to confirm that the construction and adjustment of the whole are and remain correct in this respect.

The test is made upon the whole " loop " as described above, the transmission being usually " doubled back " to enable the sending and receiving relays to be mounted close together. A stable low-frequency oscillator is used to supply the impulses, and not only drives the sending relay, but also the time base. The relays are double-throw and hence send two signal currents, termed " mark " and " space " respectively ; and the frequency of the voltage supplied by the oscillator is doubled for the time base, so that when the relay is operating symmetrically, the indications given by the two contacts occur in successive cycles and are superposed. An extra delay in the operation of one of them will hence cause two separate indications to appear on the screen.

In this instance, however, no indication is visible until one or other of the contacts is broken, as the anode voltage of the oscillograph is derived from the secondary of a transformer, the primary windings of which are connected to the relay contacts in series with a battery. At each " break," therefore, a voltage kick occurs, in the right direction to energise the spot, which moves instantaneously towards the centre of the time circle and back again, tracing a short radial line. A typical result is shown in Fig. 98, in which there are two such lines, indicating the presence of an abnormality.

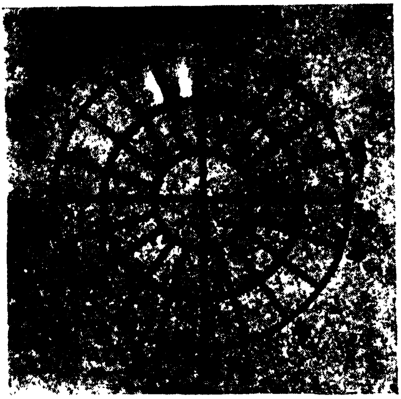

FIG. 98.—Distortion test on telegraph system.

The sending relay is first made to operate the receiving relay direct, no distortion being registered ; and then the telegraph loop is introduced between them. Both radial lines will move round by some angle equivalent to the delay time of the circuit introduced, but if they are still coincident, no distortion is present over the loop. If, however, the radial lines are now separated, the displacement angle is proportional to the percentage distortion of the loop. For example, frequency distortion will result in the " marking " time decreasing and the " spacing " time increasing, and therefore the two radial lines will move away from coincidence. A circular scale is attached to the oscillograph screen, which enables difference angles to be read off and expressed as a percentage distortion.

12. DISTORTION IN RADIO RECEIVERS. Reference has already been made in Chapter VI to the differential method of testing for distortion. More information can be obtained in many cases by employing the linear time base to trace the shape, first of the input wave from an oscillator to a component of a radio set, and then of the output from that stage. These are recorded in juxtaposition on the same film, enabling a comparison to be readily made. The process is facilitated

if the two waves are on about the same scale, and a potentiometer or similar adjustment is generally used, especially in the case of amplifying stages, as shown in the diagram of the previous test.

**Use of the Double-beam Tube.** 12A. DISTORTION—(*contd.*). The above test could be made with somewhat greater certainty and convenience by employing a double-beam tube, which enables the two records to be obtained simultaneously.

13. FREQUENCY COMPARISON. For certain purposes, frequency comparison can also be carried out most effectively by means of the double-beam tube. Measurement of the temperature/frequency coefficient of an oscillator forms an interesting example. It is important to know how the frequency given by one of these apparatus is affected by a specified change of temperature ; or the same information might be required with regard to change of battery voltage. According to this method, a stationary wave from a standard oscillator is impressed upon the screen by means of one pair of plates, and a second wave from the oscillator under test by means of the other plates. Any difference between the frequencies is indicated by the second wave moving horizontally with respect to the first. The time taken to travel exactly one cycle is measured by means of a stop-watch, and is the period during which the test oscillator has gained or lost one cycle, the direction of drift indicating whether the result is " fast " or " slow." The most exact timing can be obtained when the two traces are brought into close juxtaposition, as shown in Fig. 99, an adjustment that can readily be effected with these instruments.

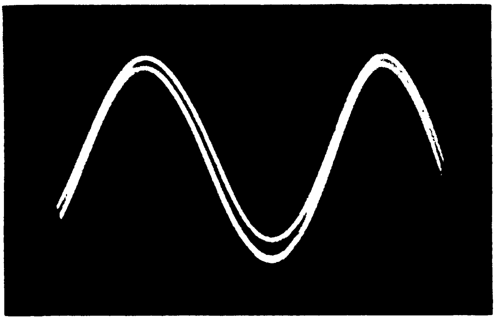

FIG. 99.—Twin waves from double beam tube for measuring frequency.

The usual method of measuring the error, apart from the cathode oscillograph, is by the counting of voltmeter beats, which suffers from the defect that it does not show whether the test result is fast or slow.

14. PHASE SHIFT. Change of phase angle in a stage of a radio set or other apparatus can be estimated by a method very similar to the

above, by connecting the input to the Y1-plates, together with a suitable oscillating voltage of the required frequency ; and the output to the Y2-plates. The linear time base is adjusted to give two standing sine-waves, which are arranged with coincident axes. Then the phase shift can be measured by means of the fine graticule placed in front of the screen. Special precautions are obviously necessary if there is any possibility of the shift being greater than 360°.

15. ECHO DETECTION. The measurement of distances to a conducting body is carried out by sending out a radio impulse and registering the time taken for the wireless echo to return. Examples of the process occur in the important investigation upon the variations in the height of the Heaviside and Appleton layers that has been carried on during the past decade at the Radio Research Laboratories at Slough.*

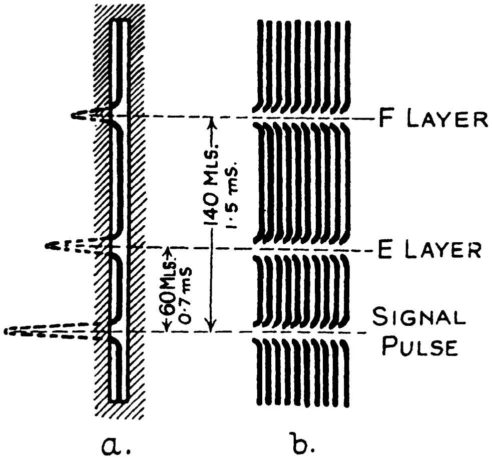

FIG. 100.—Detection of echoes from Heaviside (E) and Appleton (F) layers. (*a*) masking of oscillogram ; (*b*) part of record showing 10 successive traces.

Now the normal heights of these layers above sea-level are approximately 60 and 140 miles (100 and 230 km.) respectively, and the times taken for the signal to reach them and return are hence about 0·7 and 1·5 ms. The problem involved in maintaining a continuous check on the respective heights can therefore be visualised. Signals are sent out in quick succession from a transmitter set up at some little distance from the receiver, which accordingly registers the arrival of the signal and the two echoes at intervals corresponding to their remoteness.

Detection is carried out by a gas-focussed oscillograph, with linear time base which is calibrated by means of a 750 c/s oscillator at hourly intervals, each cycle thus representing 400 km. of equivalent height. The transmitter is triggered by the 50-cycle mains voltage, giving out an impulse every 0·02 sec., and by controlling the time-sweeps of the oscillograph in a similar manner, the sending and receiving arrangements are easily synchronised. It is then only necessary to amplify the incoming signal and supply it to the Y-plates of the oscillograph, and to photograph the trace at the required intervals.

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* See *The Cathode Ray Oscillograph in Radio Research*, by Watson Watt, Herd and Bainbridge Bell (H.M. Stationery Office), p. 110.

The camera shutter is operated automatically every 30 seconds. Suitable exposure times are from $\frac{1}{10}$ to 1 sec., superposing from 5 to 50 successive exposures upon the film. The latter is of the " paper negative " type, and is slowly traversed sideways, so that the records are very close together. As is frequently the case with steep movements of the spot, the nearly vertical parts of the peaks are almost invisible ; but as all the desired information is afforded by the gap in the straight portion of the trace, the peaks are removed altogether by photographing the screen through a mask in which a narrow slit is cut. The result is as shown in Fig. 100, from which the convenience of the record and economy in photographic material are evident.

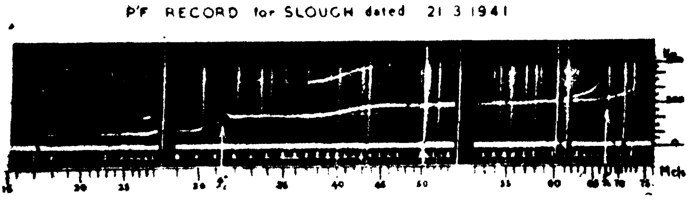

FIG. 101. Variation in apparent height of E and F layers. Typical P'f* record for the equinox period in South-East England illustrating the variation of height of reflection with frequency for vertical incidence transmission. The record shows the critical penetration frequencies for region E ($f_E$) and for region $F_2$ ($f_{F_2}$) as discontinuities.

* P'f = equivalent path as a function of frequency.

An actual record taken at Slough is shown in Fig. 101.* In this case the frequency of the signal was steadily increased from about 15 to 75 Mc/s in a short period on one particular day, the spring equinox of 1941 being chosen. Two discontinuities in the record are marked, occurring at the critical penetration frequencies for the E and $F_2$ layers respectively.

The above method is now well known to be the basis of Radiolocation, and can obviously be employed to detect, locate, and even examine conducting bodies in the atmosphere or in non-conducting space. Many applications of the principle can therefore be expected in the very near future in connection with sea and air navigation, the safety of transport generally, and similar functions.

Further, it is capable of making the same determinations as regards cavities and other flaws in liquid or solid conductors and insulators if a supersonic sound signal is substituted for that produced by radio, the rest of the scheme remaining electronic. By employing two similar quartz crystal diaphragms for the transmitter and receiver respectively, the transition from radio to supersonic and back again is easily effected.* The chief requirement is that the frequency shall be high enough to produce reflections and shadows from the flaws to be detected, which

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* Reproduced by permission of the director of the N.P.L.

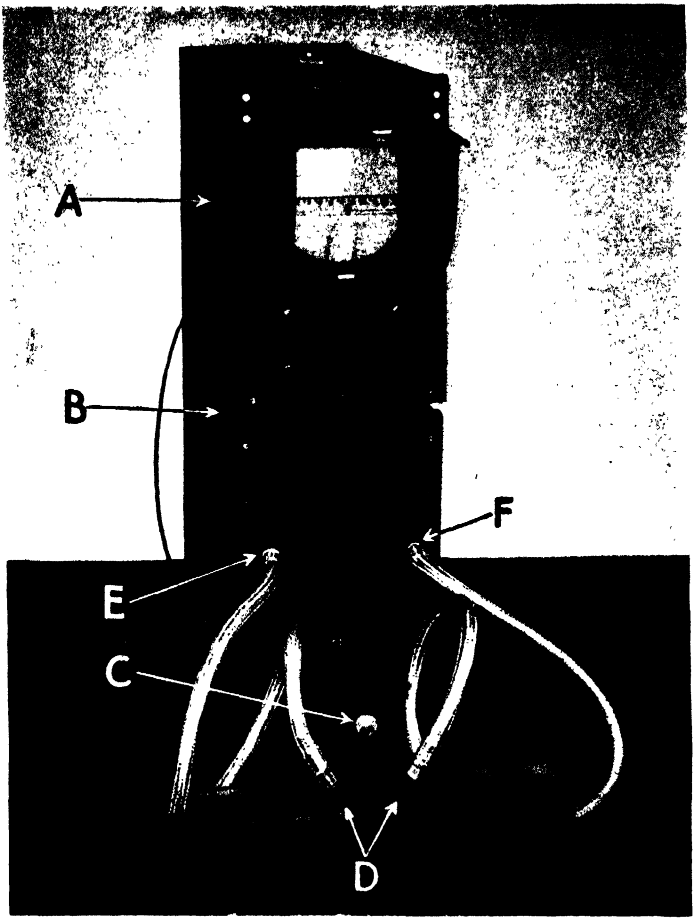

FIG. 101A. Supersonic flaw detector (Hughes). A. Tube unit. B. Control unit. C. Thumb screw. D. Adapting wedges. E. Receiving quartz sockets. F. Transmitting quartz sockets.

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* See Appendix D, last par. but one.

means that the wave-length must be small in comparison with the dimensions of the flaw.

In the supersonic flaw detector made by Henry Hughes (Ilford) a frequency of 2·5 mc/s. has therefore been chosen. This apparatus, which will readily indicate even small flaws in forgings and nearly all castings, forms an interesting example of flaw-location, and is shown in Fig. 101A. Here the cathode oscillograph unit is standing upon the

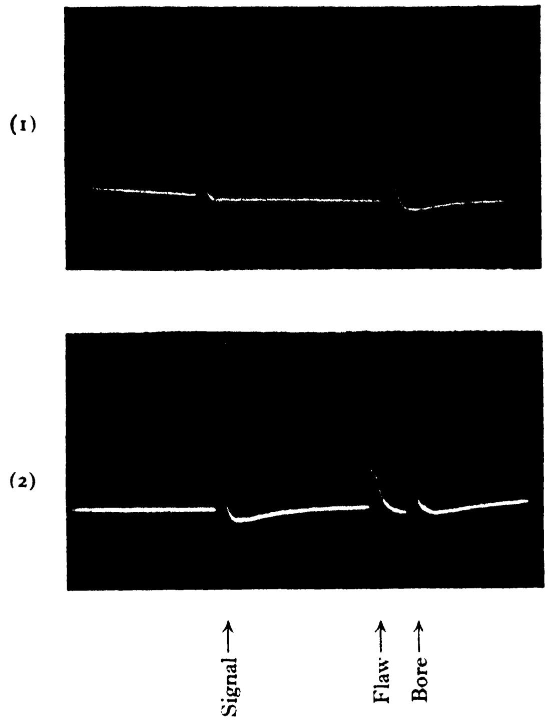

FIG. 101B.—Oscillograms from cylindrical forging, showing reflection only from central bore in (1), but in (2) a reflection also from a flaw.

control box, containing the triggering circuit, transmitter driver and amplifier. In front are the transmitter (left) and receiver (right), consisting of the crystal diaphragms, 2 cm. in diameter by about 0·1 cm. thick, contained in flat cylindrical metal capsules, which are mounted upon wedges having the correct angle to the surface of the metal under test.

The operation of the detector is exemplified by the oscillograms in Fig. 101B. Again the peak on the left is the pulse sent out by the transmitter, which again is triggered with relation to the time base, and now affects the receiver by electromagnetic induction. The distant peak on the right is the reflected signal from the far boundary of the article under test, which was in this case a heavy cylindrical iron forging ; while the intermediate pulse in the second oscillogram is a reflection from a small cavity. So sensitive is the scheme that voids the size of a pin's head are registered. The distance from the surface is ascertained by scaling along the time-base, as in Fig. 100 ; while the exact lateral position and the size of the defect are readily deduced from successive indications by an operator who has had a relatively short experience at the work.

Wedges are unnecessary when a curved surface is under treatment. For a smooth surface, such as one formed by turning, the best results are given by smearing it with fairly thick oil, in order to assist in transferring the pulses from capsule to surface and *vice versa*. Tin amalgam is used for a rough " natural " surface. Cast iron is one of the few metals for which the apparatus is unserviceable, on account of the graphite flakes it contains.

16. POINT-BY-POINT TESTS. For certain purposes, such as plotting the characteristic curves of thermionic valves, a somewhat higher degree of accuracy is required than can be obtained by tracing the complete curve on the fluorescent screen ; for it must be remembered that the size of the diagram is limited, and any error due, for example, to thickness of trace or trapezium distortion will hence produce an effect that may prove undesirable. While, therefore, the all-oscillograph method is ideal for certain valve-development purposes, more exact results are needed in other kinds of valve research. But although a point-by-point method is used, other advantages of the cathode oscillograph, such as safety to the operator and avoidance of overheating, filament bombardment, and similar drawbacks that accompany the purely static method, are too valuable to sacrifice.

A highly satisfactory compromise has been evolved by Macfadyen and Day,* whereby the cathode oscillograph is employed to plot the characteristic curve of the valve under test ; the normal anode and screen voltages being applied, with sufficient negative grid bias to suppress the space current. Then the grid is driven up to the desired voltage by means of an alternating potential, the time base of the oscillograph being employed to show up the peaks of anode current. It should be remarked that the important measurement is that of the current at the peak of the grid voltage cycle, which is not necessarily the maximum current. The point at which the determination is required having been selected, a steady voltage is applied in series with the A.C. voltage in order to shift the significant point on the curve back to the zero line. The magnitude of the " shift " voltage, which can be read off with great accuracy, is a measure of the required value of anode current.

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* See " A Dynamic Valve Test Set," *Journal of Scientific Instruments*, xvi, October, 1939, p. 324.

There are a number of practical details in connection with the scheme that are worth noting. A zero line is readily applied to the screen by attaching a thread to the glass by means of two small pieces of plasticine. Voltage measurements are made with a slide-back voltmeter, which keeps its deflection after the voltage is switched off and can be read off at leisure. A frequency of 200 c/s was used in preference to 50 c/s, partly because smaller smoothing condensers could be used, partly to obtain a steadier oscillogram, and partly to enable any " hum " due to the 50 c/s filament-heating current to be readily detected. The arrangement of the apparatus is shown in the diagram forming Fig. 102, in which the segregation of the high voltage components in an earthed metal case, in order to ensure safety for the operator, will be observed. A L.V. gas-focussed tube may be employed.

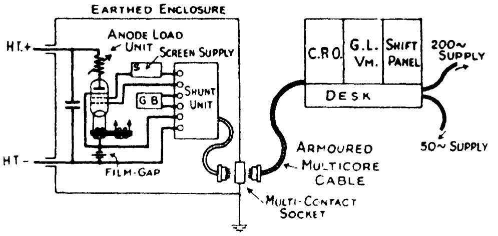

FIG. 102.—Arrangements of units and protective enclosure for point-by-point test for valve characteristic.

17. GALVANOMETERS. Mention was made in Chapter V of the use of the cathode ray tube as a galvanometer, only one pair of deflectors being employed. There are, however, certain advantages in applying a fluctuating voltage to the horizontal plates even when measurement of the vertical movement, without regard to time or other independent variable, is the main requirement ; and this practice is frequently adopted.

The simplest reason for adding a horizontal movement to the spot is that it is easier to read, especially when it is brought to a fine focus ; and the reaching of a true null value can hence be observed more accurately. Further, there is less risk of damage to the screen when a line rather than a point is being traced.

In some cases, however, useful supplementary information can be secured by virtue of the additional movement. A specially interesting example is afforded in a recent Schering bridge investigation by the E.R.A. Certain discharges through oil impregnation were being studied, a gas-focussed cathode ray tube with amplifier being used as a detector. A horizontal sweep derived from the mains unit was first employed, with phase-angle adjustment that enabled the sweep to be

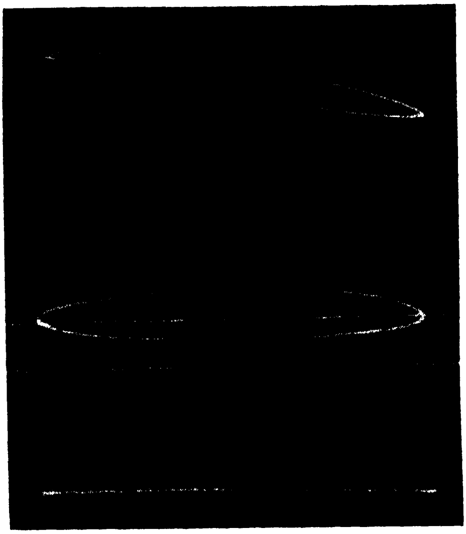

FIG. 103. Elliptical trace of bridge detector.

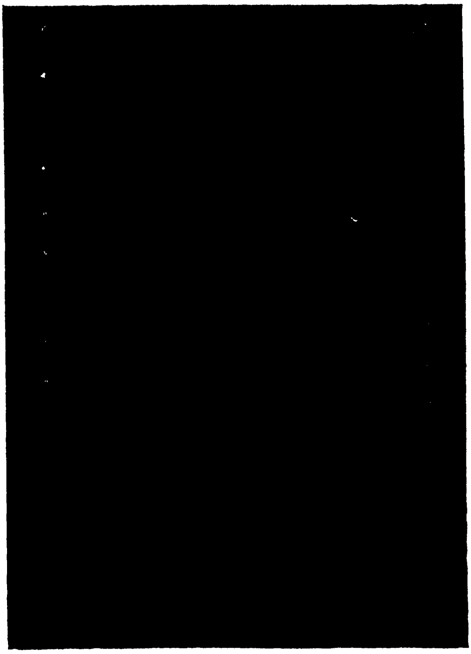

FIG. 104. Helical trace of bridge detector.

kept in phase with the voltage across the pure resistance arm of the bridge resulting from a capacity unbalance.

Then whereas a complete balance is represented by a horizontal straight line, phase-angle unbalance is shown by a horizontal ellipse, and capacity unbalance by an inclined straight line. These are exemplified by the traces in Fig. 103. It will be seen that the additional information enables the adjustment of the in-phase and out-of-phase components of the bridge to be effected independently and with greater certainty. Further, a simple calibration enables the phase angle of the dielectric under test to be read off directly; since an ellipse with a semi-minor axis equal to the separation of the two parallel straight lines would indicate a phase angle given by $\tan \delta = 0{\cdot}01$. The ellipse in the middle of the figure thus corresponds to a value for $\tan \delta$ of 0·005.

These were, however, not the only advantages resulting from the sweep. When a certain voltage, viz., about 15 kV per mm., had been applied to the specimen, a corona discharge began, showing itself by a succession of small vertical voltage kicks in the oscillograph figure. In order to study their occurrence for a number of cycles in succession, a steady vertical component was added to the sweep, producing the helical figure shown in Fig. 104. The corona here is shown in a very graphic manner, appearing to " drip " off the turns of the helix.

The sensitivity of this cathode ray detector was such that the capacity could be balanced to 1 part in 5,000, and a P.F. of 0·0002 detected.*

## PART II

## Recurrent Surges

The principles involved in the production of recurrent surges were described in Chapter IV. A typical 250-volt " surge," obtained in this instance from the recurrent surge generator illustrated in Figs. 54 and 55, is shown in Fig. 105, and should be compared with an actual " lightning " surge of 100 kV from a Marx-type generator as given in Fig. 112 of the next chapter. This and the following record were taken with an ordinary camera possessing an f/4.5 lens and a diaphragm shutter, requiring an exposure of only 2 seconds for a standard ortho film.

**Use of Recurrent Surge Oscillograph.** Applications of the recurrent surge generator and oscillograph include tests on the distribution of surge voltage in transformer and alternator windings, the effects of surges in cables (such as the values of the transit time and surge impedance), and the performance of surge protection equipment. It is also available for recording the transient conditions existing in certain classes of circuit at the instant of making or breaking current by means of various devices. Typical examples are described below.

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* See E.R.A. Report Ref. L/T107, published under the title, " Discharges in Insulation under A.C. Stresses," by A. E. W. Austen and S. Whitehead, J.I.E.E., Vol. 88, Part II, pp. 88–92.

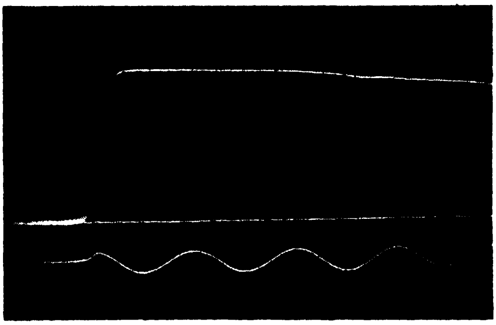

FIG. 105.—Typical surge, having amplitude of 250 volts, produced by recurrent surge generator. Timing wave 100 kc/s.

The importance of tests of this description arises from the effect of the different conductors in modifying the surge. Every conductor functions more or less as a condenser, which must be charged by the surge before it can pass on its way ; and every insulating medium can introduce losses which gradually dissipate the travelling wave. Two adjacent turns of a winding, for example, constitute a capacity across which a large portion of the surge voltage may be concentrated during the instant of charging ; so that the end turns are especially liable to break down upon the arrival of the impulse. It is hence very desirable that the designer shall know how the wave is modified as it reaches various parts of the winding.

FIG. 106.—Voltage from mid-point to earth of coil of 4,000 kVA booster transformer, when surge in Fig. 21 was applied to high-voltage end. Timing wave—100 kc/s.

Overhead and underground cables possess a continuous capacity to earth and also between adjacent cores ; while the energy in the surge is continuously absorbed by corona in air-insulated, and dielectric losses in solid and liquid insulated lines. Again it is of importance to know how far the wave has to travel in various types of cable before the wave-front and amplitude are modified to a specified extent.

17. TRANSFORMER WINDINGS. The surge in Fig. 105 was applied to one end of a 4,000 kVA booster transformer winding, the other end being earthed. A record taken from its mid-point tapping by means of the B.T.H. recurrent surge oscillograph is shown in Fig. 106, which indicates the voltage conditions to be met by the designer at this part of the winding.

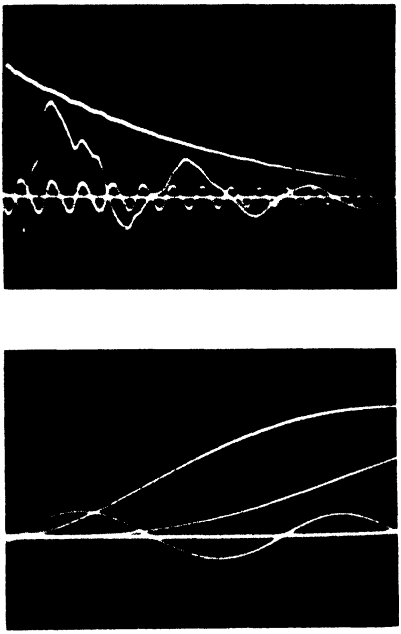

FIG. 107. Records of applied surge and oscillations in a transformer winding. Two traces were taken simultaneously in every case. Timing waves—100 c/s. (upper) and 1 Mc/s (lower).

The two examples in Fig. 107 were taken by the E.R.A. instrument, which is able to record three traces simultaneously ; but in the present cases the voltage at the point under test and the zero line were first imprinted, and then the applied impulse and the timing wave. Both show a 1/50 wave applied to a transformer winding, forming the upper trace, and below this the corresponding voltage to earth at a point within the winding situated 63 per cent. from the line terminal for the upper figure and 6·6 per cent. for the lower ; the neutral being earthed for the upper and insulated for the lower. The timing waves, however, differ, being 100 kc/s for the upper figure and 1 Mc/s for the lower ; and the great extension of the horizontal scale with the much more rapid sweep is strikingly shown. For the latter figure an exposure of 6 seconds was given, involving the superposition of 300 traces ; in spite of which no unsteadiness whatever is observable.

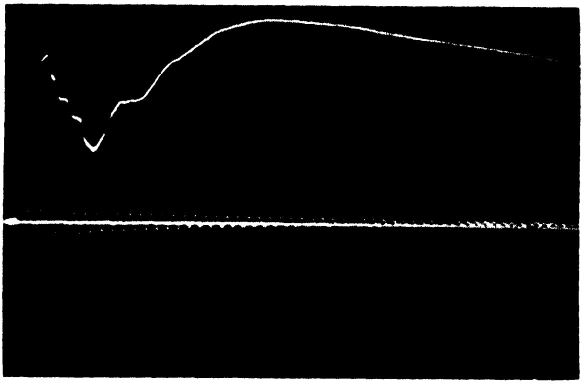

FIG. 108.—Voltage at distant end of concentric cable.

18. INSULATED CABLE. An oscillogram taken during an investigation into the effects of transient transfer phenomena in a cable is shown in Fig. 108. The cable was a 660-volt triple concentric paper-insulated type specially designed for metering purposes. A surge resembling that in Fig. 105 was applied between the central core and earth, and the record was taken at the distant end. A B.T.H. oscillograph was used.

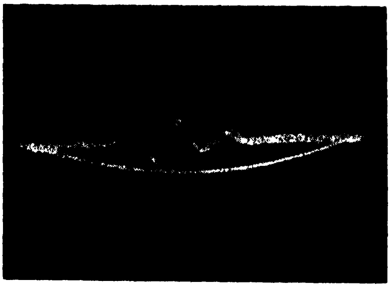

FIG. 109. Sparkover of ignition plug (48 superimposed traces).
Timing wave (lowest curve) 1 Mc/s.

19. IGNITION SPARKOVER. The final example (Fig. 109) is a record

by the E.R.A. apparatus of the oscillatory current consequent upon the plug sparkover of a magneto ignition system. It is a very high-speed oscillogram, the timing wave being only a half-wave of a 1 Mc/s oscillation, so that the whole record represents only 0·5 $\mu$s. This oscillogram consists of forty-eight superposed traces, and is interesting as an example of the recording of uncontrolled recurrent impulses. Tripping of the sweep and recording of the current were both effected by the voltage drop across a 6-ohm resistance connected between the body of the sparking plug and earth ; the connections to the vertical deflectors being taken through 200 yds. of Telcon delay cable, the function of which is described in section 1 of next chapter. The oscillogram shows that the spark had a peak value of about 60 amps. and a frequency of 14 Mc/s.

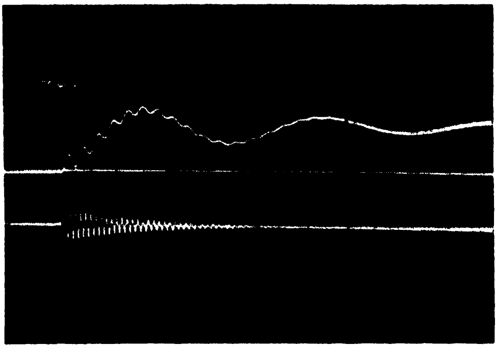

FIG. 110.— Restriking transient due to low-impedance generator and high-impedance transformer. Timing wave 100 kc/s.

**Use of Restriking Voltage Indicator.** An explanation of the origin of the restriking voltage wave, and of its importance in circuit-breaking, will be given in the next chapter, in connection with the actual full-scale short-circuit tests, the effects of which it is the purpose of the B.T.H. instrument to simulate. The example given below will enable a direct comparison to be made between the high-power conditions and the low-power reproduction.

19. OIL CIRCUIT-BREAKER. The oscillogram shown in Fig. 110 was taken by the staff of the B.E.A.I.R.A. at the terminals of a breaker controlling a low-impedance generator and a high-impedance transformer, each of which has contributed its natural frequency component to the re-striking transient. An oscillogram taken during an actual breaker operation will be shown in the next chapter, and the close correspondence between the two records will serve to illustrate the accuracy of the present apparatus.

## CHAPTER EIGHT

# TESTS REQUIRING A SINGLE-SWEEP TIME BASE

Both observation and photography are much more exacting when the phenomenon observed takes place once only, than when it recurs continuously for as long as desired. Much more care has to be taken in order to secure a sufficiently enduring impression in the tests now to be described. For observation purposes, a fluorescent screen with a long afterglow is of considerable assistance ; while to obtain a satisfactory photographic record from a glass tube oscillograph, the most actinic " blue " screen, coupled with a super-sensitive film and wide-aperture lens, will be necessary. For the higher writing speeds, the metal tube oscillograph with the film inside the vacuum possesses considerable advantages as regards sensitivity over the glass tube. Great improvements have, however, been effected in the latter in consequence of the demands made by the television receiver, and for the majority of purposes, even including the photography of high-speed transients, the metal tube no longer has the field to itself. Special interest therefore attaches to the type of tube employed, particulars of which will accordingly be given in connection with each application.

1. LIGHTNING SURGES. There is no doubt that our knowledge with regard to the nature and behaviour of lightning and other surges has increased very greatly within recent years, an advance which has been largely due to the exact information as regards test results afforded by the cathode oscillograph. A phenomenon that can take less than a millionth of a second to reach its climax was obviously beyond the capabilities of the metering equipment in use two decades ago, and all research and testing now carried out upon lightning arresters, transformers under surge conditions, impulse generators, switching transients, or similar investigations, include a cathode tube as an essential part of the test plant.

Tests involving lightning surges are carried out for two main purposes : first, to investigate the nature of the lightning stroke itself and its effects upon electric transmission lines, windings, and materials, and secondly, to test the effectiveness of arresters and other devices designed to protect against the effects of a lightning discharge. For the former class of test, the surge figuring in the investigation may be either the natural discharge* from a thunder-cloud, or one artificially produced by a surge generator ; but for the latter class it would always be artificial. As would be expected, the carrying out of the tests is much simpler when the " lightning " can be generated at will ; and as there is no difficulty in designing apparatus that will give a controlled impulse wave reproducing the effects of the natural surge and having predetermined characteristics, the man-made discharge is used in the great majority of cases.

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* See Schonland and Elder, " Anticipatory Triggering Devices for Lighting and Static Investigations," *Jour. Franklin Inst.*, January, 1941, p. 39.

Surge generators are based upon the Marx circuit, the principle of which is indicated in Fig. 111. When a unidirectional voltage is applied to the " busbars " marked + and –, the condensers C,C . . . are all charged in parallel through the high resistances R,R . . . , until the voltage across their terminals reaches a sufficient value to spark across the diagonally connected sphere gaps. The condensers are thus connected in series, and discharge across the large sphere gap G at a potential equal to *n* times the charging voltage, where *n* is the number of condensers or " stages " ; of which there are four in the figure. As the time of discharge is of the order of a micro-second and the resistors are of the order of a megohm each, no appreciable amount of the discharge can be by-passed while the spark is in being.

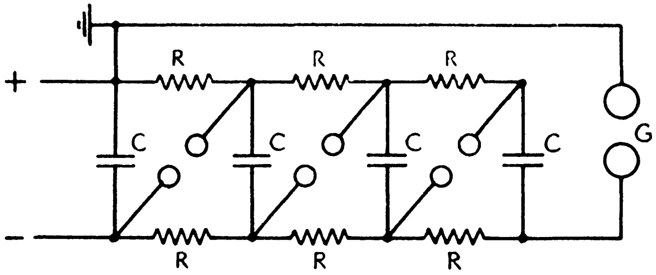


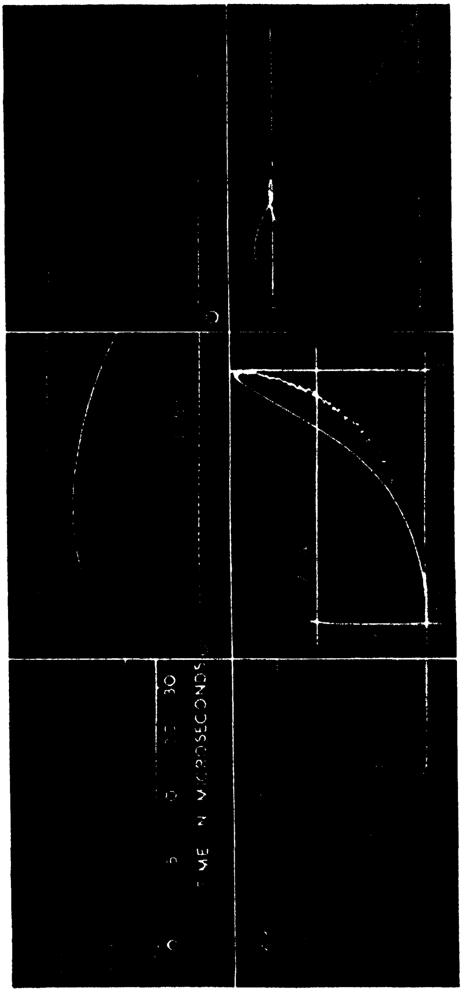
FIG. 111.—Four-stage surge generator.

In a typical example, the applied voltage is derived from a power transformer followed by two large rectifying valves in a voltage doubler circuit, providing 160 kV at the condenser terminals. There are sixteen stages, giving a maximum impulse voltage of 2,560 kV, or somewhat over 2,500,000 volts. By means of variable capacities and resistances, the " front " and " tail " of the wave can be varied to conform with standard waves, or other desired conditions ; while the voltage and capacity of the discharge can be regulated by connecting the stages variously in series, series-parallel, or parallel as required.

A typical " lightning " surge, recorded by means of a continuously evacuated tube, is shown in Fig. 112, in which the crest voltage of 100 kV is reached in 0·6 micro-sec., and the wave falls to half its maximum value in about 20 micro-secs. This would be termed a 0·6/20 wave.

The information required from the tests is chiefly as follows :

(*a*) The exact description of the test wave, and in particular the duration of the front and tail ; also the rate at which the voltage increases up to the instant when the arrester begins to pass current. This last is specified to be 100 kV per micro-second per 11 kV of rating.



Figs. 112–117.—Reading from top left to right: Fig. 112, 100 kV, 0·6/20 impulse wave from surge generator. Fig. 113, high voltage surge relieved by lightning arrester. Fig. 114, current-time wave through arrester. Fig. 115, voltage-time and current-time curves, for 1,500 amps., peak current. Fig. 116, voltage-current curve. Fig. 117, voltage-time and current-time curves, for 15,000 amps., peak current.

(*b*) The period that elapses before the arrester begins to pass current, and the voltage at which this occurs.

(*c*) The maximum voltage " left on the line " while the arrester is passing a specified current, such as 1,500 amps. This is the maximum instantaneous voltage following the initial " sparkover " of the arrester.

(*d*) The voltage at which the arrester ceases to pass current.

(*e*) The current/time oscillogram must show that the current reached a value such as 1,500 amps. in a specified time, usually 10 micro-secs, and decreased to half that value in a further period equal to the former.

(*f*) Following a specified series of 30 surges of 1,500 amps. at 1-minute intervals, a final oscillogram must show that the arrester has not deteriorated during the test. The curves must be smooth, with no sudden breaks or changes of slope ; and the final oscillogram must conform satisfactorily with the initial record.

Particulars such as those suitable for satisfying the first half of (*a*) have already been scaled off the surge in Fig. 112. For the remaining oscillograms a much higher voltage wave was used, and is shown in Fig. 113 as far as the early part of its front is concerned ; but it is then cut short by the operation of the arrester under test. This oscillogram enables the latter part of (*a*) to be answered, the voltage increasing at the rate of 180 kV per micro-second. The information under (*b*) is also contained in Fig. 113, the arrester beginning to pass current in 0·6 micro-sec. at 94 kV.

The current/time oscillogram in Fig. 114 was taken by means of a " hair-pin " shunt in the main discharge circuit, with the generator at the same setting as for the voltage/time curve in Fig. 113. By scaling this curve it is confirmed that a current of 1,500 amps. was reached in 10 micro-secs, which decreased to about half value in a further 10 micro-secs. The conditions in (*e*) are therefore satisfied, and the voltage/time curve (Fig. 113) can again be employed to satisfy (*c*) and (*d*). A maximum voltage of 110 kV was reached subsequently to the peak indicating sparkover, while the voltage corresponding to current zero is shown by Fig. 115, which contains both voltage and current curves, to be 29 kV.

Before and after the 30 surges of 1,500 amps., current/voltage curves resembling Fig. 116 were taken. This oscillogram was actually obtained at the conclusion of the tests, after six further surges had been passed, each exceeding 15,000 amps., and recorded as regards both current and voltage by oscillograms similar to Fig. 117. The final current/time curve in Fig. 116 showed that the characteristics of the arrester had not deteriorated as a result of the very heavy surges that it had relieved.

The chief characteristic of these tests is the extremely short periods of time during which each action takes place. Two main problems are thus imposed, namely, the great sensitivity required for obtaining the photographic record, and the highly accurate timing needed to synchronise the operation of the oscillograph with the inception of the surge. With regard to the first, it may be stated that, by using every possible care, the glass tube type has in the past been just capable of recording a lightning surge ; but there was so little margin, and in consequence so little flexibility and so much uncertainty, that the metal tube oscillograph was practically always employed. The records in this section were taken with an oscillograph conforming quite closely with that in Fig. 2 and exemplified by that in Fig. 4 (except for the drum), or in Fig. 51. Examples later in the chapter will indicate the capabilities of the modern glass tube for this work.

Timing difficulties are less when the generation of the surge is under the control of the experimenter than when a natural lightning stroke initiates the impulse. Three operations have normally to be carried out within a period of about a micro-second, and not only in the correct sequence but correctly spaced in time. These are the untrapping of the spot, the starting of the sweep, and the release of the surge. More than one method is available, but the scheme preferred by the author is shown in Fig. 29 (Chapter III).

To begin with, the surge is released by tripping the surge generator, usually by connecting to earth the middle member of a three-sphere spark-gap forming one of the discharge gaps which has been modified for triggering the others. Near the generator a short aerial, shown at B in the figure, is set up, which is likewise connected to the middle sphere of a spark-gap ; and this initiates the breakdown of the whole gap, short-circuiting the + and — leads. At once the voltage across the trip deflector plates collapses, and the beam is untrapped and passes down the tube. At the same time the condenser begins discharging through the resistances R, R and reducing the voltage between the sweep plates, deflecting the beam across the tube at a speed that decreases exponentially. Thus the spot is traversed rapidly during the steep wave-front, but at suitably lower speeds during the long-drawn-out tail.

So far the timing is not all that could be desired, if the surge generator be assumed to be connected directly to the " vertical " deflectors ; for the surge begins slightly before the untrapping of the beam, with the result that some at least of the wave-front will fail to be recorded. The arrival of the impulse at the deflector plates is therefore retarded by being led through a roundabout route of sufficient length, in the shape of a " delay cable." A retardation comparable with the duration of the wave-front, or about one micro-second, is sufficient ; and since the speed of light (and electricity in an air-spaced conductor) is 300 metres per micro-second, about this length of conductor is usually inserted. It is, however, important that, to avoid distortion, air-insulated cable be used either in the form of two concentric brass tubes, the outer of which is about 3 in. in diameter, arranged in zigzag formation on the walls or ceiling, or else the more recently introduced " Telcon " rubber-sheathed air-spaced cable.

An alternative method is to trip the beam first, and arrange for this operation to trip the surge generator ; but somewhat more complication is involved thereby. A further variant is to omit the trap deflectors altogether, and to energise the cathode at this stage instead. The focus of the spot, however, alters considerably when the beam is first switched on, and it is customary to adjust the concentrating coil immediately before the record is taken. No real increase in complexity results from the use of the trip plates, while the switching on of about 60 kV D.C. to start the record is to be avoided where not essential.

FIG. 118.—Electromagnetic oscillogram of a heavy short-circuit (16,890 amps., [peak]) on a 1,500 MVA, 132-kV circuit-breaker.

A more recent scheme, used in conjunction with a glass tube oscillograph, is described in section 5 later.

2. CIRCUIT-BREAKER RE-STRIKING VOLTAGES. When a large circuit-breaker, whether of the oil-immersed, gas-blast, or other type, is caused to rupture a short-circuit, the final break occurs at a zero point in the current wave, and consists in the prevention of the arc from re-striking and executing a further half-cycle. An electromagnetic oscillogram showing the fluctuations of the current and voltage during such an operation performed by a 1,500-MVA, 132-kV oil circuit-breaker rupturing its full capacity, is given in Fig. 118. It will be evident that the important action has taken place at the point C, but no indication is given as to what exactly has happened owing to the periods and frequencies involved being far beyond the capability of the oscillograph that traced the record.

Now what has been going on during that and the previous zero pauses is a conflict between the voltage across the gap on the one hand, and the de-ionisation of the arc space on the other. At the earlier zero points, as the separation of the contacts was increasing, the length of the arc and therefore its cooling and de-ionisation were insufficient to resist the voltage, and the arc consequently re-struck. But at the final point the de-ionising process triumphed. It needed, however, the cathode ray oscillograph to show exactly what had occurred. The record reproduced in Fig. 119 was taken simultaneously with the previous oscillogram and effectively supplies the missing information.

The fluctuation of the voltage wave can now be clearly seen. Its main course on the complete oscillogram is determined almost entirely by IR drop across the resistance of the arc ; but as the wave reverses through the zero points, it begins to oscillate at the natural frequency of the circuit, in the present case about 6,250 cycles per second. If the upward rush past the zero is quick enough, it will be able to rekindle the arc before de-ionisation has gone too far ; but at C it was unable to do so, and the oscillation consequently died gradually away and merged in the " recovery " voltage, which is the normal system voltage, somewhat reduced by the effects of the short-circuit. The slope of the voltage at reversal, or the " rate of rise of re-striking voltage," is the important criterion, which the cathode oscillogram is employed to reveal.

FIG. 119.—Cathode ray oscillogram showing voltage fluctuations at point C in Fig. 96. The three nearly straight sloping lines are 50-c.p.s. voltage waves.

Owing to the length of the record, and the uncertainty as to the point at which extinction will occur, the time base is nearly always provided mechanically by a rotating drum. Two instruments so equipped, which were incidentally responsible for Figs. 119 (Cambridge) and 121 (Met.-Vick.), were shown in Fig. 52, Chapter IV. The taking of the record is quite simple, the trap plates being merely switched off and on at the appropriate time by the pendulum or sequence drum controlling the whole test on the breaker.

A method has, however, been devised by the Electrical Research Association, employing their electron relay * system of triggering a time base, whereby the voltage phenomena in the neighbourhood of (*i.e.*, just before and after) successive current zeros can be recorded on a small stationary photographic plate, as in Fig. 120. The method enables the selecting and triggering to be effected with such accuracy that the records of voltage around successive zeros can be located at any desired position on the plate, even where current zeros are unevenly spaced by thousands of micro-seconds owing to displacement of the neutral axis. A much more open time base can be employed than with the revolving drum, since the film velocity is limited in the latter case by the high centrifugal stresses at the higher speeds.

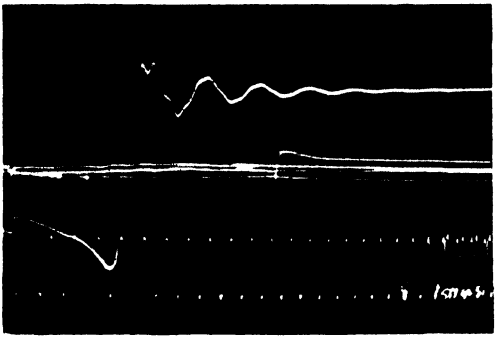


Fig. 120.—Arcing and restriking transient located by exponential time base Timing wave 100 kc/s.

The example in Fig. 120 shows the voltage at an arcing zero (small figure) and the restriking voltage (large outside figure) of a small experimental breaker. A metal tube oscillograph was used, and the time base is nearly linear over the range employed. The timing wave is 50 kc/s, and two natural frequencies will be detected, viz., 100 and 20 kc/s.

Before the film is loaded into the drum casing of the oscillograph it is important that all moisture be removed from both celluloid and gelatine, and this is effected by preliminary insertion in a desiccating-box, such as that seen at the bottom of Fig. 52. The film is attached to its drum, but is left rather slack to allow for shrinkage as the celluloid dries out, and the whole is put into the cylindrical container, which is arranged to be evacuated through a phosphorus pentoxide or other suitable drying filter. Considerable time can be saved when necessary by using two drums alternately.

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* See A. M. Cassie, *Proc. Phys. Soc.*, Vol. 46, September 1st, 1934, p. 721.

An example of an investigation carried out with one phase of the MV oscillograph is given in Fig. 121, which shows how the re-striking voltage changes as the current increases in a 33-kV gas-blast circuit-breaker. Short-circuits amounting to 2,630, 7,000, and 11,500 R.M.S.

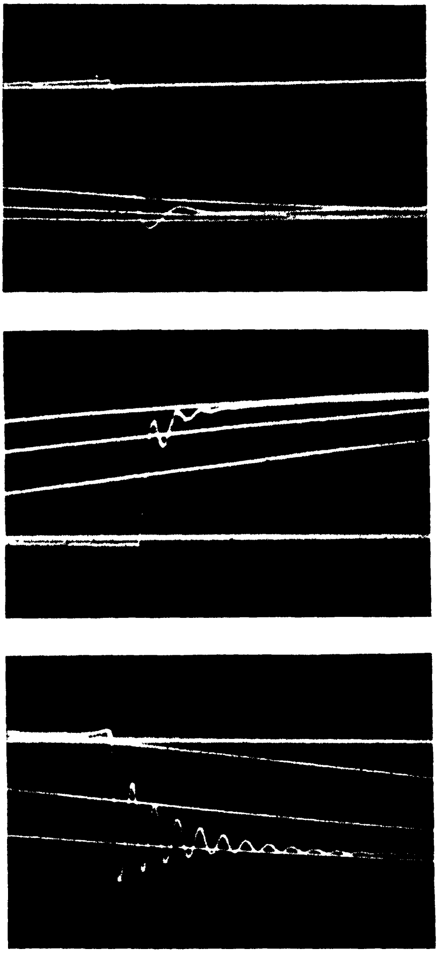

FIG. 121.—Three restriking waves given a 33-kV gas-blast breaker, at 2,630, 7,000 and 11,500 RMS amps., respectively; rates of rise being 432, 725 and 1,690 volts/μs.

amps. respectively at 29 kV (*i.e.*, about 1·5 times the rated phase voltage) were broken by a single phase of the breaker, and the oscillograms indicate the effects of post-arc conductivity at the three currents. Whereas there was only a single alternation in the top wave, there are three distinct cycles in the middle and about twelve for the highest short-circuit current.

Although the continuously evacuated tube possesses obvious advantages for re-striking voltage and natural frequency records, the work is now actually within the capabilities of the sealed-off (glass) tube, which can be employed when special considerations, such as portability, turn the scale in its favour.

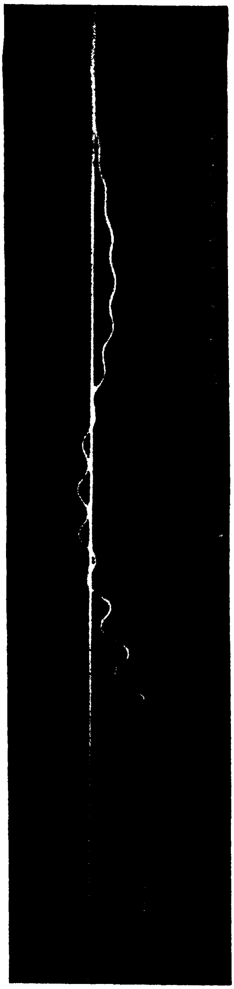

FIG. 122.—Final arcing and restriking wave on system fed from high-impedance generator through low-impedance transformer. Taken on drum-type multi-element glass tube oscillograph.

An oscillogram taken with this instrument in the form illustrated in Fig. 48, Chapter IV, is shown in Fig. 122, recording the re-striking voltage on a system fed from a relatively high-impedance generator through a relatively low-impedance transformer. Two natural frequencies can be clearly identified, viz., one of about 3·6 kc/s due to the generator, and one of about 37 kc/s due to the transformer. The faint trailing luminosity is caused by the afterglow, although with the "blue" screen this is extremely short. The clearness and large scale of the trace indicates the great advance that has been achieved by the high-vacuum tube employed.

3. SURGES IN TRANSMISSION LINES. It is important to know how surges communicated to or induced in transmission lines behave as regards attenuation and reduction of front angle with length of travel. Tests were made on several lines forming part of the British Grid by the staff of the Electrical Research Association in order to provide such data. Of these the most important was the investigation carried out upon the 132-kV feeder between Reading and Portsmouth, 47½ miles in length.

A surge generator of twelve stages, capable of giving an impulse voltage of 1,300 kV, was set up in Portsmouth Sub-station, and a metal tube continuously evacuated cathode ray oscillograph was taken to four points along the line in succession to record the shape of the surge after passing through the various lengths of feeder. Two of the points were at the extremities of the line, and the other two were 0·97 and

2·94 miles distant from Portsmouth respectively. The oscillograph was connected to the line conductors through a capacity potential-divider of 100 micro-microfarads. Some of the surges were applied equally to all three phases, but most interest attaches to those led into only one phase conductor, and to the surges induced in the adjacent phases by these parent waves.

The nature of the single-phase surges applied to the line at Portsmouth is expressed by the symbol 1/5, *i.e.*, the crest value of the voltage was reached in 1 μs, and it fell to half-value in 5 μs from the start of the surge. This shape was recorded by the oscillograms taken at Portsmouth, and the waves as modified by corona and resistance drop were indicated by the readings at the other points along the line.

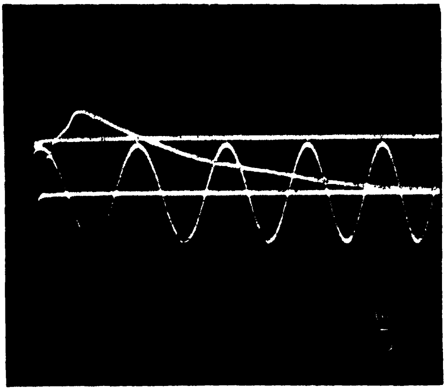

FIG. 123.—Parent wave from surge generator 2·94 miles away on 132-kV grid line. Timing wave—20 kc/s.

Typical examples are given in Figs. 123 and 124, which were recorded at the 2·94-mile location.

In the first of these the attenuated parent wave is indicated, the values being readily scaled off with a knowledge of the calibrations, of which the most obvious is the period of the timing wave, viz., 50 μs. The initial shape of the wave being as given above, it is seen that the position of the crest had been retarded from a point 1 μs from the start to 3·5 μs, giving a front that is much less harmful to any windings it may encounter. The amplitude had also decreased from an initial value of 494 kV to 296 kV.

The form of the induced wave in one of the other phases is shown in Fig. 124. Less attenuation has occurred in this case, owing to the absence of corona loss, the corona limit of the line being 250 kV. Thus the retardation of the crest has only been from an initial lag of 1 to 4 μs, and the attenuation was from 105 kV at the commencement of travel to 70 kV at the 2·94-mile location. But the most interesting feature of the induced wave is the initial reverse loop, which was quite marked at this position on the line.

Calculations had previously been made whereby the behaviour of the various waves had been predicted, and the most valuable result accruing from the tests was the confirmation of the methods of calculation that had been employed.[*]

4. ARC RESISTANCE. In the course of researches upon the arc accompanying the rupture of an A.C. short-circuit, one of the important factors which require to be measured is the rapid variation in the arc resistance within a period of about 50 micro-seconds around current zero. Considerable difficulty is experienced in making this measurement by direct estimation of the arc voltage and current, especially if it is to include the period immediately before the zero point. A method has therefore been devised by the E.R.A.[†] for passing a high-frequency current through the arc and recording the H.F. voltage-drop across it by means of a metal tube oscillograph. The amplitude of this H.F. voltage-drop is then converted into a measurement of resistance by the application of an appropriate calibrating factor.

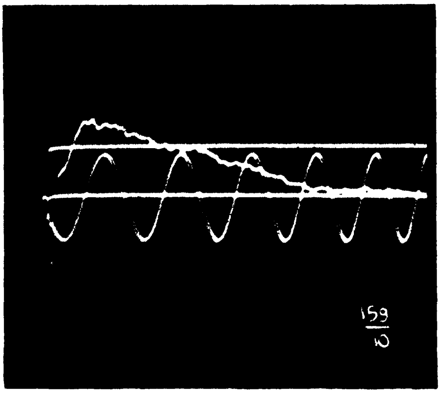

FIG. 124.—Induced wave on adjacent phase conductor. Other particulars as in previous figure.

A typical record is shown in Fig. 125, in which the variation of arc resistance in a circuit-breaker is continuously indicated by the amplitude of the superposed H.F. voltage-drop due to current produced by an oscillator giving a frequency of nearly half a million c/s. The re-striking voltage-wave is of quite normal shape with a natural frequency of about 8 kc/s, and the superposed H.F. is shown very distinctly in spite of its high periodicity. The locating of the required record on a small photographic plate was achieved by use of the E.R.A.'s electron relay referred to elsewhere.

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[*] See *Surge Phenomena* (B.E.A.I.R.A.), p. 183.

[†] See *The Electrician*, February 17th, 1939, p. 206 : A. M. Cassie, F. O. Mason, and L. H. Orton.

5. TIME-LAG OF SPARK GAPS. An example is now given which illustrates very recent practice in the use of the sealed-off tube. It will have been gathered that one of the factors upon which the recording speed depends when a fluorescent trace is being photographed is the speed of the film, and with this is bound up the photographic technique employed in the development and general processing of the image. Considerable improvements have been effected in this technique by Messrs. W. Nethercot and H. Beattie of the E.R.A. towards the end of 1941, with the result that the capabilities of the glass tube have been still more extended, as shown by the following three oscillograms.

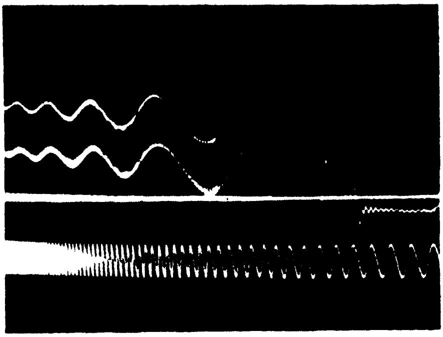

FIG. 125.—Measurement of arc resistance by means of H.F. oscillation. Time R to h. Timing wave—100 kc/s.

These are all *single-sweep* examples taken by means of a " Transient Recorder " sealed-off oscillograph operating at an anode voltage of 5 kV, described in Chapter IV, pp. 59/60. The first two, forming Fig. 126, are waves having frequencies as high as 5·5 and 24 Mc/s ; while the third, forming Fig. 127, gives the result of a test to ascertain the time-lag between two high-voltage low-current spark-gaps in series. The sloping trace records the voltage on the high-voltage cable between the two breakdowns, the time-lag being of the order of a few microseconds.

It will be of interest to work out the writing speed on the basis of the lower record in Fig. 126. As the length of each cycle is about 0·8 in., and there are $24 \times 10^6$ of these per second, the total travel is about $1{\cdot}6 \times 10^6$ ft., or 300 miles, per second.

6. ELECTROCARDIOGRAPH. A new era was introduced in connection with the examination of the human heart when the discovery was made that it develops a regular cycle of voltage fluctuations which can be

recorded by means of leads held in the subject's two hands, or connected between the right hand and left foot, or between the left hand and left foot; these three connections giving the voltages developed across the base, long axis, and left border of the heart respectively. At first (*i.e.*, from 1903 onwards), the Einthoven string galvanometer was the only instrument available for recording the fluctuations; but the cathode oscillograph now forms a very successful alternative.

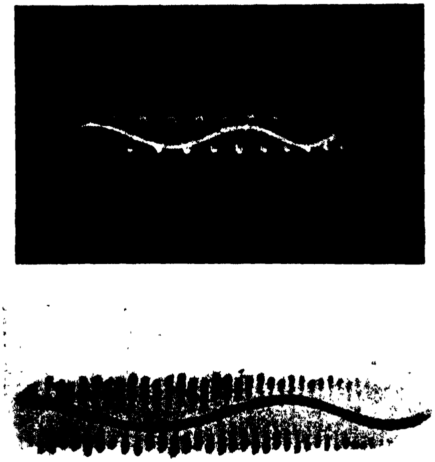

FIG. 126. 5·5 (upper) and 24 (lower) Mc/s waves.
Timing waves—1 Mc/s.

FIG. 127.—Voltage on H.T. cable between two spark-gaps in series. Duration—5·5 μs.

Cardiograms are always taken as single-sweep records, since successive wave-forms are usually irregular when disease is present; while although a repeating time base is employed for observation, the periodicity is low and in reality each cycle is examined individually.

A typical heart oscillogram is shown in Fig. 128, which was made by means of the Cossor-Robertson portable electrocardiograph, and is characteristic of a healthy heart-beat; though the reason for the fluctuations is not yet fully known. The pattern is, however, modified in a definite manner by the various diseases, which can hence be detected with certainty even when in an incipient stage. In all the oscillograms the vertical scale is 1 mV per cm., and the horizontal scale half a second per cm.; and these values will enable any desired information to be scaled off as regards the magnitudes of the voltages or time intervals.

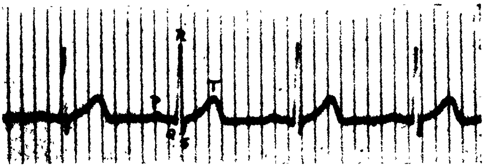

FIG. 128.—Normal heart oscillogram.

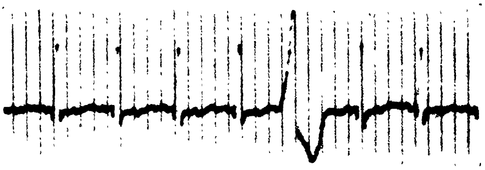

FIG. 129.—Oscillogram of diseased heart-beat.

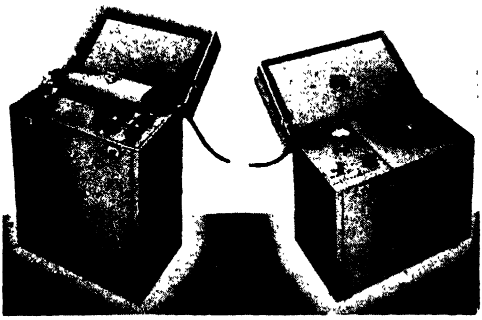

FIG. 130.—Cossor-Robertson cathode-ray electrocardiograph (left) and mains unit (right).

An example of the change produced by a diseased condition is shown in Fig. 129, which is characteristic of auricular flutter throughout, with ventricular extrasystole at the fifth peak. Both this and the previous figure were taken by means of the first arrangement of leads, viz., between the hands ; but tests would be made and probably records taken by means of all three, as the information given is then much more complete. The electrodes whereby connection is made to the hands or feet consist of metal discs which are covered either with pads of absorbent material soaked in a strong saline solution, or with electrode jelly. The electro-cardiograph itself is shown in Fig. 130.

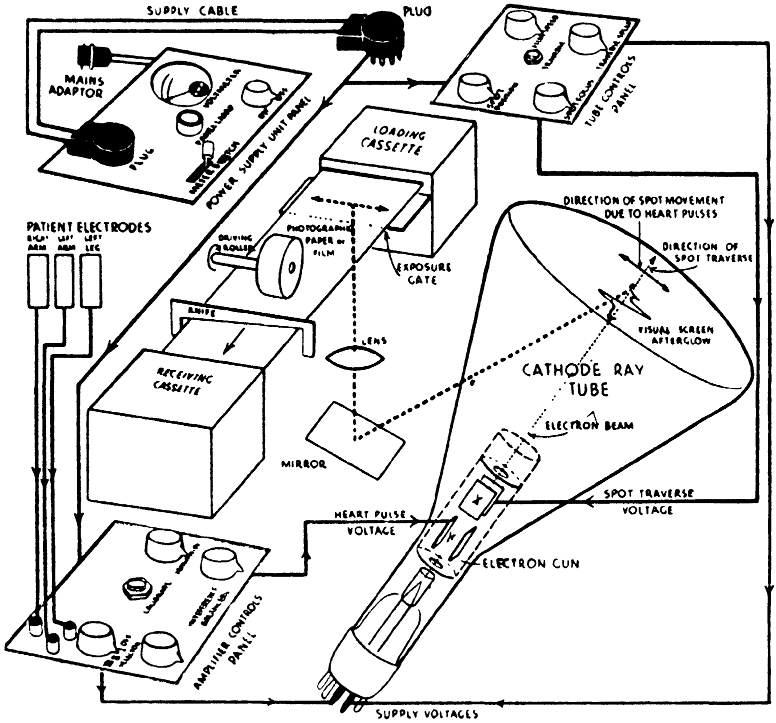

FIG. 131.—Arrangement diagram of internal parts and controls, Cossor-Robertson cardiograph.

For purposes of observation, a time base of the usual type is provided ; but when records are required, as in the last two figures, only the " vertical " pair of deflectors are used, and a clockwork mechanism feeds a strip of photographic negative paper past the screen and lens at a speed of 2 cm. per second, as shown in the diagram forming Fig. 131.

Photography is carried out through the glass of the tube, upon the inner side of the screen, thus enabling the beam to be watched while the exposure is taking place. A knife is fitted whereby the exposed length of paper can be cut off, unloaded in daylight, and taken to the dark room for development.

A definite advantage of the cathode oscillograph over the galvanometer is that the results are immediately available by observation, and do not have to wait until the film is processed. Its negligible loading completely avoids polarisation difficulties in the saline pads, and together with its lack of inertia secures absence of distortion under all working conditions. Portability and robustness are also inherent features, and are especially important in the case of observations for which it is often advisable to take the instrument to the patient and not *vice versâ.*

Time is marked upon the records at 0·1 sec. intervals by a pendulum device. The apparatus is built into two easily portable cases, shown in Fig. 130, containing the power supply unit and the recorder unit respectively, the former constituting either an A.C. mains " eliminator " or two 300-volt high-tension batteries. A gas-focussed oscillograph tube is used with a " blue " fluorescent screen giving several seconds' green afterglow. The special advantage of this screen has already been described on p. 17.

Medical science will make a much greater use of the cathode ray oscillograph in the near future. To begin with, the above apparatus is readily capable of extended powers as soon as the demand exists. It can be made even more compact than at present. It can be used to obtain the vectorial composition of three simultaneous heart voltages on a " triograph." Further, the instrument could be used as an encephalograph, nerve reaction recorder, or blood pressure register; while, if a double-beam tube were used, it could record heart voltages and heart sounds simultaneously.

Encephalograph connections are usually made by means of six electrodes which are held in place by rubber strips forming a net to fit the head. Two are located on the forehead, two on the middle and two at the back of the head ; one of every pair being on the right and the other on the left. Then four voltages are recorded by the oscillograph, namely, between the front and top and between the top and back electrodes on each side.

As regards the nature of the brain voltages, the normal values are from 1 to 200 $\mu$V, at frequencies ranging from 1 to over 50 c/s ; the normal being about 16 kc/s. A mental effort, such as a calculation, causes the voltages to disappear until quiescence returns. The absence of one of the voltages while the patient is relaxed generally indicates a brain tumour between the corresponding electrodes, and by moving these close together, the exact position of the tumour can be found.

Contact is made with nerves by means of needles or wires.

A recent application of the cathode ray oscillograph to surgery may serve as an example of developments that are taking place at the present time. This is for indicating the progress of nerve rehabilitation following an operation, in which it has been used to record the first microscopic movement after the ends of the nerve had been stitched together.

7. YOUNG'S MODULUS AND VIBRATION FREQUENCY. It is frequently necessary to ascertain the value of Young's modulus for constructional materials, including not only metals such as steel, but also stone, brick, tiles, asbestos, cement, and mortar. The traditional method is that employing the extensometer, which is not a very speedy one and demands a considerable amount of care. Further, the shape of the specimen required for this test is one which is often difficult to obtain with building materials. Rods or cylinders of from 7 to 14 in. in length are readily prepared ; and a simple method of measuring the frequency of longitudinal vibration by means of the cathode oscillograph has been worked out by Grime * for samples of this shape. Now Young's modulus (E) is accurately given for such rods by the equation :—

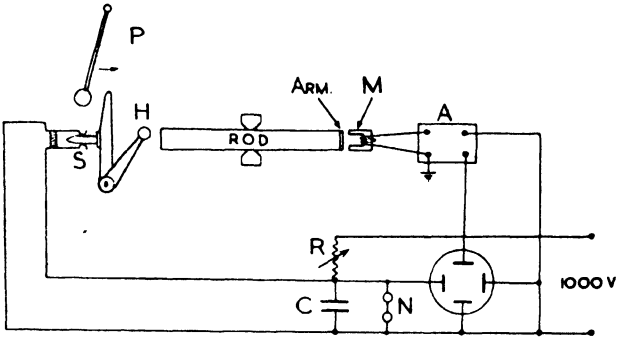

FIG. 132.—Determination of Young's modulus by longitudinal vibrations.

$$E = 4l^2n^2\rho,$$

where $l$ = length of rod,
$n$ = frequency,
and $\rho$ = density.

Since both $l$ and $\rho$ can be easily measured, the determination of $n$ enables the value of the modulus to be at once found.

The arrangement of the apparatus is shown in Fig. 132. Wooden jaws grip the rod at the middle of its length and support it in a horizontal position. Longitudinal vibrations are set up by a light hammer H, impelled by a blow from the pendulum P, which at the same time opens

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* See *Phil. Mag.*, Ser. 7, Vol. 20, August, 1935, p. 304.

the switch S and thus removes the short-circuit across the sweep condenser C. The latter is then charged at the desired rate through the adjustable resistance R, and traverses the spot horizontally across the screen at a nearly linear velocity, until the neon lamps N strike, which, by limiting the condenser voltage to about 300 volts, terminate the single sweep.

A soft iron armature, $\frac{1}{32}$ in. thick, is cemented to the right-hand end of the rod, and is thus vibrated close to the poles of a small U-shaped permanent magnet fitted with a suitable coil. The mechanical vibration is therefore transformed into an alternating voltage, which is magnified by the amplifier A and applied to the vertical plates of the oscillograph. Voltage peaks from an oscillator (not shown) are also injected into the input of the amplifier, causing short peaks to appear on the record at intervals of a milli-second. It is hence a simple matter to measure the frequency from the resultant oscillogram to within 0·5 per cent. For the complete determination of Young's modulus, allowing for 0·3 per cent. errors in the measurement of each of the other quantities, the maximum possible error is 2·1 per cent.

Owing to the rapidity with which these small specimens can be tested, a large number can be dealt with in a relatively short time, enabling comparisons to be made between specimens that have been exposed to different treatments. A further advantage derived from the multiplicity of tests is the possibility of applying statistical methods and hence securing greater accuracy.

### CHAPTER NINE

# TESTS INVOLVING INDEPENDENT BASES OTHER THAN TIME

The class of tests involving deflections due to two quantities other than time are interesting and important for several reasons. In the first place, they belong to the most general species of determinations in which the change in an independent variable constituting the cause is plotted against the resultant change in a dependent variable. Secondly, of all tests this class is the most beyond the capabilities of the electromagnetic oscillograph. A special instrument known as the cyclograph was in use, which deflected the beam of light in two directions at right angles to each other, and consequently electromagnetic records with respect to any other horizontal scale than time were called " cyclograms." There is no need to perpetuate this term in the present connection, when the one instrument is capable of tracing curves upon any base ; and it has been dropped by the author. Tests now under consideration are greatly used for research upon, and the proving of, materials and apparatus, and a valuable opportunity is hence afforded for the breaking of fresh ground, whereby investigations that have in the past been difficult, lengthy, and inaccurate may now be carried out easily, rapidly, and with exact results.

The most common examples are those in which variations in current are caused by a prescribed series of changes in the voltage. Such cases will probably already have occurred to the reader, in which curves that have had to be plotted as a result of step-by-step measurements can now be not only tabulated, but also automatically traced on the screen or film in a small fraction of a second. Economy of time is particularly striking when the test has to be repeated for a number of samples or articles, or adjustments of the same circuit or apparatus ; while the special capabilities of the instrument in most cases render the results of additional value quite apart from the question of speed.

Other examples falling within the present category are the variations of mechanical pressure with piston travel in the case of engine cylinders ; but for convenience all determinations involving pressure as one co-ordinate will be considered together in the next chapter.

1. INDICATION OF RESONANCE. The advantages of the instrument for use with bases other than time are well illustrated in connection with the measurement of the natural frequency of a circuit or apparatus. There are several methods available, but the simplest is shown in Fig. 133, in which an oscillator connected to the circuit is caused to generate

increasing frequencies, and the oscillograph employed to detect the points of resonance. As the natural frequency is reached, the circuit resonates, and the current is then in phase with the voltage. These two quantities are connected to the two pairs of deflectors respectively, and the phase relationships between them are indicated by the series of Lissajous' figures traced on the screen. Since exact synchronism is shown by the circle or ellipse collapsing into a straight line, the indication is a very clear one.

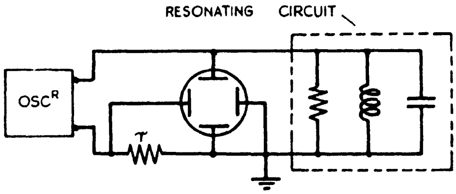

FIG. 133.—Measurement of natural frequencies.

An example of such a determination may be quoted. The method was applied in connection with a single-phase short-circuit test on an oil circuit-breaker, the network having one corner earthed. Natural frequencies were measured as follows : 25, 37·5, 52, 95, 130, 150, 178 kc/s. Some of these are obviously harmonics of the lower values.

2. MEASUREMENT OF POWER, POWER FACTOR, AND IMPEDANCE. The above principle may be extended in order to measure the angle between current and voltage ($\phi$), the power factor ($\cos \phi$), the wattless and power components, and other particulars. Since the phase angle $\phi$ is zero and consequently the power factor is unity when the figure on the screen possesses zero area, and moreover $\phi = 90^\circ$ and $\cos \phi = 0$ when the area is a maximum, this figure may be used to estimate the relative amount of "reactive" power or wattless component present. The latter is proportional to $\sin \phi$, which can be evaluated from the screen figure by two simple methods that have already been described under "Differential Tests" in Chapter VI (see pp. 85/6) ; while the same of course holds good for $\cos \phi$ and $\phi$.

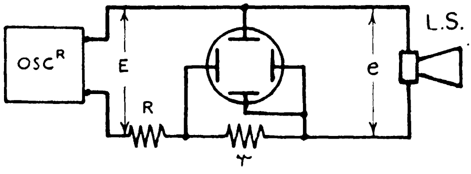

FIG. 134.—Test for impedance and power factor of loud-speaker.

One of the chief advantages of the oscillograph method of making these determinations is that they can be carried out under the actual working conditions of the apparatus tested ; for power factor and impedance in many cases depend upon frequency and other variables. An example is shown in Fig. 134, in the form of a test upon a loud-speaker. The applied voltage E is made equal to the effective anode voltage developed by the power valve with which the loud-speaker is to be used, and the resistance in the circuit, R + r, is made equal to the internal anode resistance of this valve. Then the frequency and value of E are varied, and the resultant impedance and power factor are noted.

3. THERMIONIC VALVE CHARACTERISTICS. A well-known voltage/current curve is that showing the performance of a thermionic valve by connecting grid or anode volts with anode current. The carrying out of the test is quite straightforward, the valve being set up in accordance with its usual scheme, with H.T., L.T., and G.B. batteries or their equivalent; and with an alternating voltage, registering on the horizontal plates of the oscillograph, introduced at the point where the variable voltage is to be applied. A load resistance *r* is inserted in the anode circuit of the valve, and the vertical plates are connected across it in order to register the current. The earth point will be located to suit the deflector connections, and care is necessary to avoid inadvertent cross connections. For example, it may be advisable to feed the A.C. through a transformer; and condensers should be inserted in the deflector leads as shown.

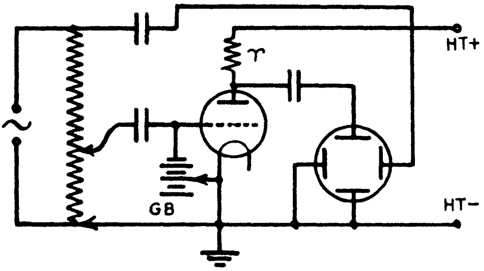

FIG. 135.—Circuit for tracing anode-current/grid-voltage curves.

Examples of these tests are given in Figs. 135 and 136, for providing the anode-current/grid-volts and anode-current/anode-volts characteristics respectively. The adjustments for grid-bias and other voltages will be observed; these are of importance in enabling families of curves to be plotted. With so convenient a method of test, very little additional trouble is required to enable a number of characteristics to be obtained covering a variety of conditions. In this way the most suitable curve can be selected for some special purpose, and the value of the various constants hence ascertained for producing the desired result. Families each consisting of three curves are shown in Fig. 137 for a tetrode and Fig. 138 for a pentode, the variable condition in each case being the grid bias.

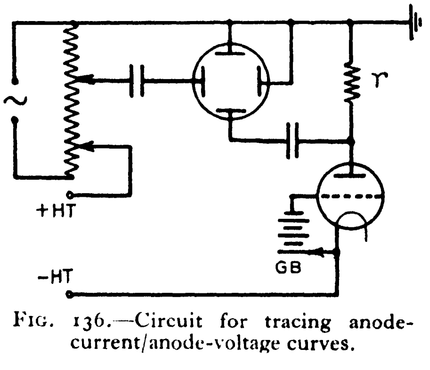

FIG. 136.—Circuit for tracing anode-current/anode-voltage curves.

Some attention is needed as regards the question of amplification in connection with the recording of families of characteristics. This arises from the fact that a valve curve constitutes a direct current, which necessitates a special form of resistance-coupled amplifier if it is to be traced in its usual position above a fixed zero line, since neither a transformer nor a capacity will pass a D.C. continuously. There is no difficulty, however, in the case of a single curve, which the instrument will " centre " on the screen in such a position that it constitutes, with the return trace, an A.C. about an imaginary neutral axis. Unfortunately it follows that curves of different amplitudes will centre themselves with their usual zero lines at different heights on the screen. Actually,

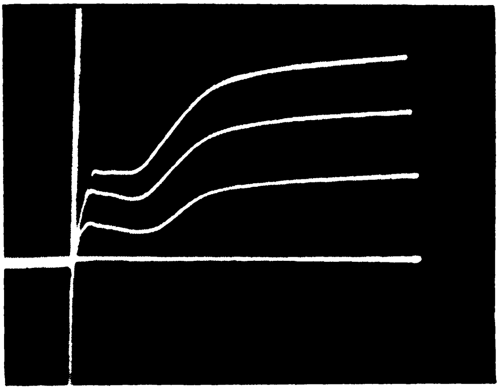

FIG. 137.—Family of $I_A/E_A$ characteristics for tetrode valve.

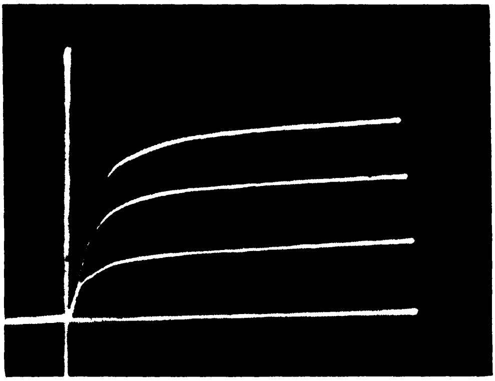

FIG. 138.—Family of $I_A/E_A$ characteristics for pentode valve.

*Note*. The upper figure (137) was obtained from the pentode of Fig. 138, with one grid cut out.

the curves in the two illustrations were all located with the aid of the vertical positioning control knob so that the horizontal axes coincided with a line marked on the screen by means of a thread and two pellets of plasticine. If it is desired to obviate this adjustment, then an amplifier such as that shown in Fig. 33 (Chapter III, see p. 43) must be employed, which is virtually a resistance-capacity type without the capacity.*

The oscillograph method confers other advantages than convenience and time-saving, one of which is safety for both apparatus and personnel. The tests should be carried out at voltages at least covering and preferably exceeding the rating of the valve under test, a common value of which is 400 volts. Not only does the point-by-point method expose the operator to a relatively high risk of receiving a dangerous shock, but it also exposes the valve to the maximum voltage for a prolonged period, whereas the oscillograph method entails only a transient application, which would normally be insufficient to cause damage. It is also a great advantage that the whole characteristic shall be visible at the same time. A method for testing valves, in which the point-by-point principle was applied with the aid of the cathode oscillograph, was described under "Repeating Time Base Tests" in Chapter VII, pp. 119/20. Reference was made in this to provisions for safeguarding the operator against high voltage.

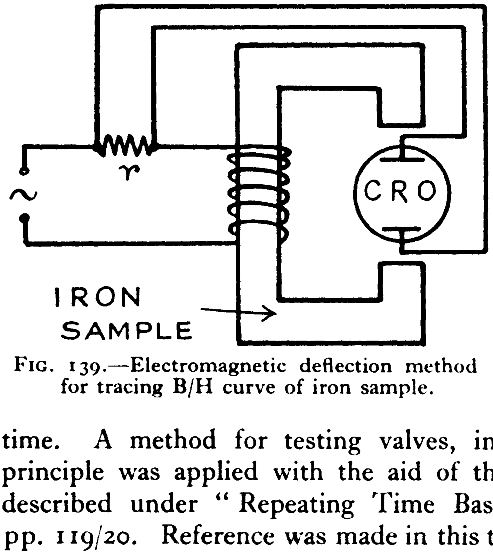

FIG. 139.—Electromagnetic deflection method for tracing B/H curve of iron sample.

4. HYSTERESIS (B/H) CHARACTERISTICS OF IRON. Very similar advantages are secured when the hysteresis loss and permeability are ascertained in the case of iron samples by the taking of a B/H curve, connecting magnetising force with the resultant flux density. This determination has been effected in the past by two step-by-step methods, employing the magnetometer and ballistic galvanometer respectively, both of which are laborious and subject to error if the greatest care is not observed throughout.

There are two general methods for delineating B/H curves by means of the cathode oscillograph, shown in Figs. 139 and 140 respectively.

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* See Millman and Moskowitz, "Tracing Tube Characteristics on a Cathode Ray Oscilloscope," *Electronics*, March, 1941, p. 36.

In the first, the flux from the sample, which is cut to a suitable shape and located so as to embrace the neck of the oscillograph, acts directly upon the beam. The current in the leads to the energising coil is led to the deflector plates, the arrangements being such that the two movements, due to B and H respectively, are at right angles to each other. The method suffers from several drawbacks, including interference with the screening of the tube and inaccuracy due to the presence of the air-gap, and it is not usually employed when exact results are desired.

The other method does not suffer from these defects, and is shown in its simplest form in Fig. 140. In this case the sample is made up in the form of a closed ring, with two windings on opposite limbs. The first is the magnetising coil, the current through which is registered on one pair of deflector plates through the medium of a resistance " shunt " r ; while the second coil develops a voltage proportional to the rate of change of the flux. Since the latter quantity is a differential coefficient, it is necessary to integrate the voltage before it is applied to the deflectors, and this is effected by the condenser-resistance combination CR. Records obtained in this way of mild steel and " Stalloy " samples respectively are shown in Fig. 141.

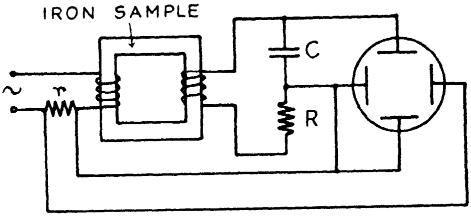

FIG. 140.—Transformer method for tracing B/H curve.

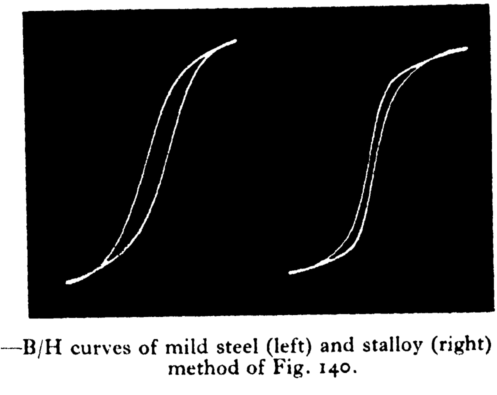

FIG. 141.—B/H curves of mild steel (left) and stalloy (right) samples, by method of Fig. 140.

The use of a closed ring avoids the considerable flux leakage that occurs with the previous method and so avoids the principal source of inaccuracy. It is an expensive shape to make up, however, and unless special arrangements are adopted the coils may have to be wound by hand on all samples. If the ring is split at two opposite corners, two former or bobbin-wound coils can be used; and if the joints are carefully fitted, any error introduced will be very small. But there will still be a small flux leakage across the window between the coils.

Both drawbacks can be countered by the modification shown in Fig. 142. The sample is now a straight bar, S, though this should be laminated as with the other methods. It is slipped through a fixed "flux" coil and then clamped up against the poles of a large-section yoke Y. Finally, the magnetising force is measured, not from the ampere-turns applied to the opposite limb, but from the voltage induced in a coil H wound on an insulating core and placed alongside the sample S. Integration is effected for both coils by $C_1R_1$ and $C_2R_2$ respectively.

A further change is made in this diagram in that the "flux" voltage is derived from both H and S coils connected in series opposition. Coil S is penetrated not only by the flux due to the core, but also by that in the whole space occupied by the coil; and if the voltage across S coil were used alone, the results would have to be subsequently corrected to allow for the second component. By making the two coils of equal size, the readings are automatically compensated for the additional flux by the series connection.

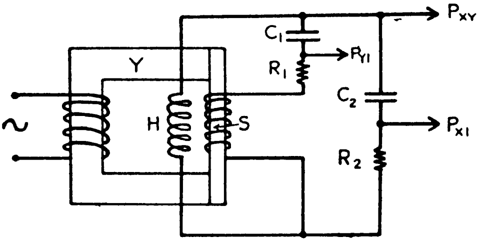

FIG. 142.—Straight bar method of tracing B/H curves.

Calibration is best effected by means of a standard sample, the curve of which is accurately known. The record in Fig. 143 shows two such curves taken at the same oscillograph setting by means of the scheme just described.

Using a 4½- or 5-in. screen, it is possible to secure results correct to within 2 per cent., the chief error arising from the scaling of the trace in these necessarily rather small-scale records. For cases where greater accuracy is required, Messrs. Siemens & Halske have adopted a differential method in their "Ferrometer," whereby a curve is obtained representing the difference between the ordinates of the test specimen and a standard sample; the subtraction being actually effected by connecting the coils belonging to the respective cores in series, with the "flux" coils in mutual opposition. In practice, the vertical gain control would be adjusted to make the difference curve fill the screen, and it is this four- or five-fold enlargement that is responsible for producing the improvement in accuracy.

It is an easy matter to construct the curve for the test sample when the standard and the difference curves are given, and this would be done when an individual test is being made ; but when a series of samples are under test, the desired information can be obtained directly from the difference curve alone.*

In addition to advantages that have already been mentioned in connection with previous examples, the above methods make their measurements with alternating current, the frequency of which may be made equal to that at which the iron under test is to be used. As the performance is not necessarily the same for D.C. and A.C., a more accurate result is rendered possible.

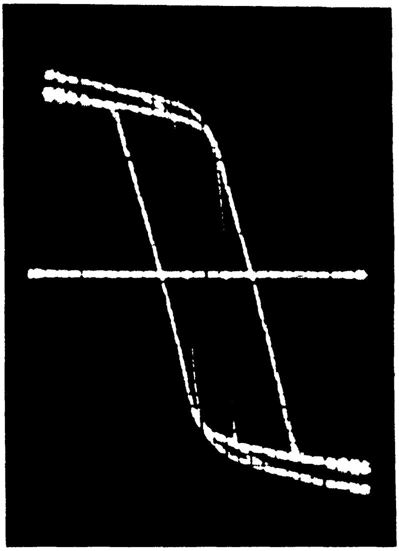

FIG. 143.—Curves for mild steel and stalloy taken by method of Fig.142.

5. STEEL SORTING. A further application of the principle just described is employed for the sorting of steel, by taking advantage of the distinctive curves that can be given by different steel alloys. Apart from the necessity of distinguishing between new material in stock, many small parts are cut from waste pieces that are themselves the leavings of previous forming operations. It is a difficult matter to prevent such material from getting mixed, and there is a demand for quick methods of identifying the various grades. Two such schemes will be described.

The first is the G.E.C. Magnetic Sorting Bridge illustrated in

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* See Chalmers and Quarrell, *The Physical Examination of Metals*, Vol. 2, pp. 18–19 (Arnold).

Fig. 144. Two identical coils are provided, which are housed in insulating cases marked respectively " Test " and " Standard." These form two adjacent arms of a bridge, the other two being the ratio resistance arms. An A.C. voltage of mains frequency is taken to the usual junctions, and the cathode ray oscillograph is connected across the bridge. The oscillograph hence registers the difference between the impedances due to the two coils at all cyclic values of the A.C. bridge current.

A standard steel specimen having been inserted in one coil and a test piece in the other, a difference figure will be given which is characteristic of the test material. The latter can then be identified by reference to a standard set of figures, four examples of which are shown in Fig. 145. Hence the apparatus not only detects the difference between the two samples, but also indicates the nature and extent of the difference.

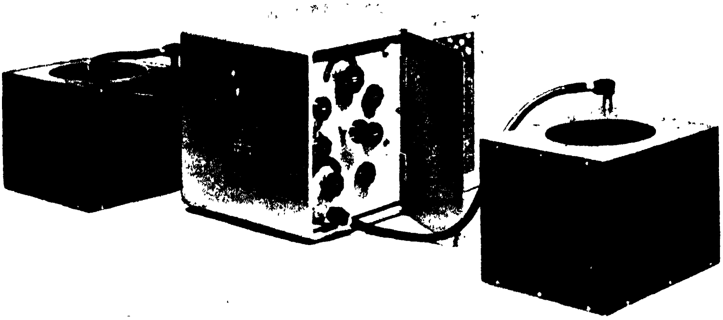

FIG. 144.—Steel-sorting bridge (G.E.C.).

The second method is a simpler one recently described by Brown and Bridle,* employing a magic eye as detector. Again there are two similar coils ; but in this case they are compound, each consisting of a magnetising and an induced voltage winding on the same principle as that used in Fig. 140. In the present apparatus, however, the two secondary coils are connected in opposition. The scheme is specially adapted for checking steel rods or bars in stock, one of the coil assemblies being slipped over a specimen of the correct material, and the other over those in turn that require checking. Then similar specimens give no indications, while an incorrect intruder causes the tube to fluoresce. The circuit is energised from the 230-volt A.C. mains.

Both the above methods can distinguish between similar materials that have received different heat treatments.

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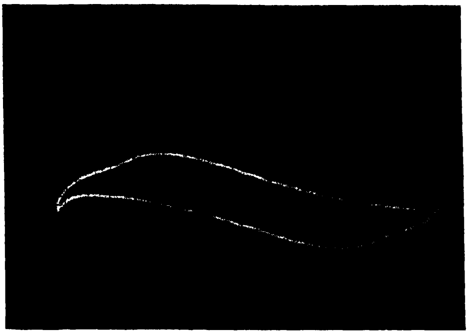
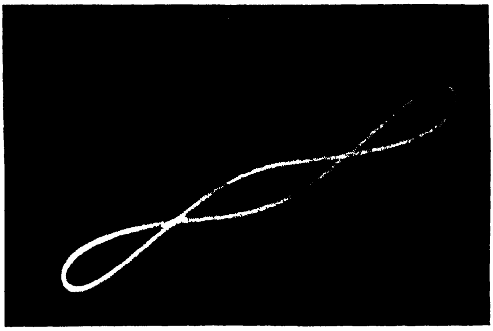
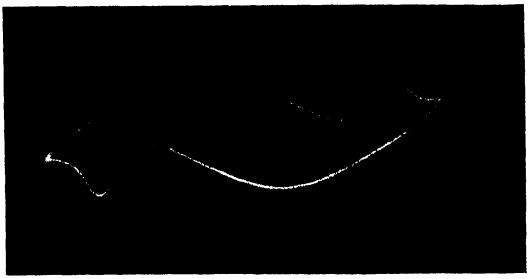
* See " A new method of Sorting Steels," *Engineer*, 3rd December, 1943.



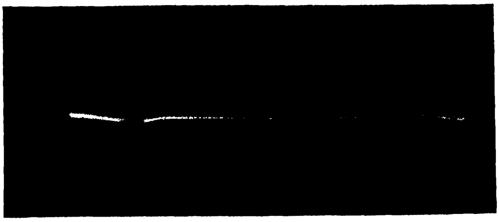
Stock steel bar.



Steel used for valve springs.



High tensile bolt steel containing 0·74 per cent. manganese.



High tensile bolt steel containing 3·6 per cent. nickel.

Fig. 145.—Typical figures from steel sorting bridge.

6. TRANSFORMER TESTING. The sample in Fig. 140 is made in the form of a transformer, although it is not intended to function as such. By using this circuit, however, an actual transformer may be tested, and the losses in the core ascertained. The method is particularly useful for the small units employed in wireless apparatus. An adjustable potentiometer will be necessary at the high-voltage terminals, as in fact may frequently be the case when the circuit is used for its original purpose.

7. VARIABLE FREQUENCY—ALIGNMENT OF RECEIVERS. The chief use of the cathode oscillograph in radio engineering is in connection with the alignment of the different stages of a receiver. This process consists of the adjustment of the tuning of each stage so that resonance occurs over the desired frequency band, and also that the resonance (or response) curve, giving the strength of the response for the various frequencies in the band, has the desired shape. For the usual receiver, the band width is 20 kc/s, *i.e.*, 10 kc/s on each side of the frequency to which the stage is tuned ; while the ideal shape for the response curve would be a rectangle described upon the 20-kc/s base. The latter shape is of course unattainable, but a close approximation is commonly achieved in the form of a curve with nearly vertical sides surmounted by two peaks, the dip between which is made as little as possible, as in the upper curve of Fig. 146.

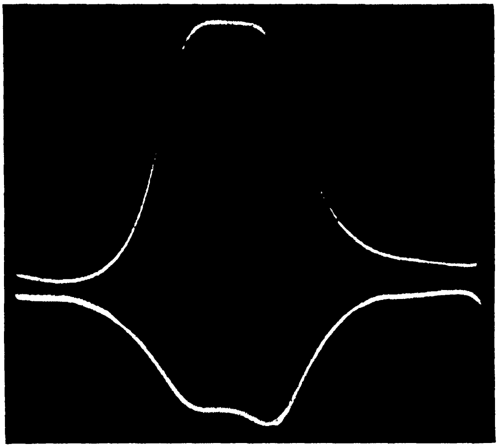


FIG. 146.—Response curves obtained during alignment of receiver.

In order to record this curve, a variable frequency base is required having a range of about 30 kc/s. To use an acoustical analogy, a " warbling " frequency or " tremulant " is employed instead of a sustained note, and would be provided in the case of a wind-driven instrument by means of a mechanically operated pulsator superposing fluctuations upon the steady pressure in the bellows. A corresponding method was extensively used for the frequency-modulated oscillators, by connecting a motor-driven variable condenser in parallel with the existing tuning condenser. Nowadays, however, a purely electrical arrangement is employed, by means of a pulsating valve, grid-controlled by the usual time base repeating at about 25 c/s. A complete equipment for receiver alignment is shown in Fig. 147.

In the tests for distortion which have been described under " Repeating Time-Base Tests," the linear time base is used to trace a curve connecting the output voltage with time, which can be compared with the corresponding input wave. For alignment tests, the " tremulant " is applied by means of the frequency modulator to obtain a curve connecting output volts with applied frequency. Then with this wave visible upon the screen, the trimming condensers and other adjustments are modified until the desired curve is given. The waves shown in Fig. 146 were taken with the above equipment, and represent the primary and secondary response curves of the last I.F. coil during alignment. The procedure described has been standard practice for years in the factory when the set is being finished off, but its use in the course of re-alignment for service purposes is much more of a novelty.

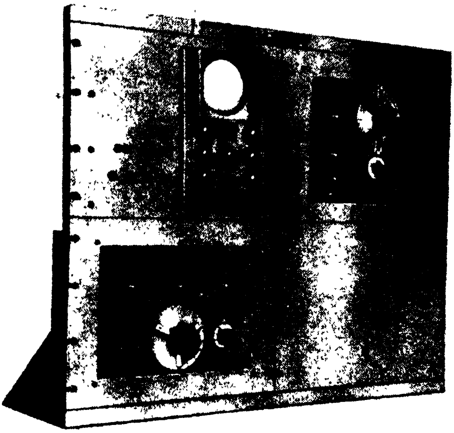


FIG. 147. Rack mounted equipment for aligning radio receivers (Cossor). The frequency modulated oscillator is below, and double beam oscillograph above it. The instrument on the right is an impedance bridge.

As with the records from other distortion or modulation tests, the operator soon acquires the art of detecting the source of the error by inspection of the test curve. In alignment tests most of the adjustments required are obvious, such as variation of the tuning ; but there are a few cases that require special note. It is most generally satisfactory to deal with the rectified and filtered wave and not with the modulated envelope before rectification. A single trace of uniform thickness is thus obtained, rendering the presence of abnormalities relatively easy to detect.

Lack of symmetry, usually shown by a hump or peak on one side of the curve, is one of the most common errors, and is caused by regeneration, or incorrect adjustment of circuit coupling. The former may be due to open-circuited or under-capacity by-pass condensers, capacity coupling or poor shielding. A fuzzy or jagged outline indicates oscillation, due to the presence of carrier current ; but it should be noted that this will also be shown by a normal receiver if connection is taken to the oscillograph from a wrong point, such as the high-voltage end of the signal diode load.

## CHAPTER TEN

# THE RECORDING OF MECHANICAL PRESSURES AND STRAINS

The recording of impulsive or high-frequency fluctuations in mechanical pressure constitutes one of the most interesting applications of the cathode ray oscillograph, since it is nearly always concerned with engineering work that has no connection with electricity. Civil as well as mechanical engineers are frequently confronted with problems which can be solved with greater facility and certainty if a graph can be obtained of the exact pressure variation in the solid, liquid, or gaseous medium involved. There are severe limitations involved in the design and use of a purely mechanical instrument for providing this information, and the electronic method has opened up new and extremely valuable possibilities, of which some of the most striking will be described.

**Pressure Converters.** There are a number of devices whereby a change in mechanical pressure can be transformed into a corresponding change in voltage. Some of these, *e.g.*, the piezo-electric and moving coil types, generate a voltage which is dependent upon the rate of movement of a diaphragm. In others, the diaphragm motion produces variation in the value of a resistance or impedance which is included in the oscillograph circuit, and a voltage source is then necessary to provide the driving power. Examples of the latter type are the carbon resistance, variable capacity, variable inductance and resistance wire strain gauge.

The most familiar pickup is the microphone, in the original form of which the resistance between carbon surfaces is altered by the fluctuation of pressure due to the diaphragm. Sound consists of a series of pressure waves in the air which can be detected by such a device, and it is well known that the microphone and oscillograph have been used with every success for tracing the wave-forms of speech and music. This work has been done with the aid of the electro-magnetic as well as the cathode oscillograph ; and also by means of other than the carbon type of microphone, such as the moving coil and condenser patterns.

The last-named and also the carbon resistance microphones have formed the bases of heavy pressure converters, or " pickups " ; while an induction type is also used, based upon the variation in the self-induction of an iron-cored coil when a keeper is moved to and from its poles. The most self-contained scheme is, however, provided by the piezo-electric effect, by which very compact and effective pickups are operated. These various types will be described in some detail.

Each pattern has its own advantages, which render it more suitable for some purposes than for others, the frequency of the pressure-waves being one of the principal criteria. For such purposes as engine indication, the movement of the diaphragm usually averages about 0·0005 in., and should not be more than 0·001 in., so that inertia is not a serious matter. Nevertheless, the induction type, in which the moving part consists solely of the diaphragm, is at an advantage in this respect. The induction and capacity types both measure the rate of change of pressure and not directly the pressure itself. Such a diagram may be preferred for some purposes ; for example, it enables the start of detonation in internal combustion engines to be more clearly distinguished than the plain pressure wave. The amplifiers used with these pickups are therefore arranged to give " velocity " diagrams when required ; but are also equipped with a resistance-capacity integrating arrangement to produce the usual pressure record.

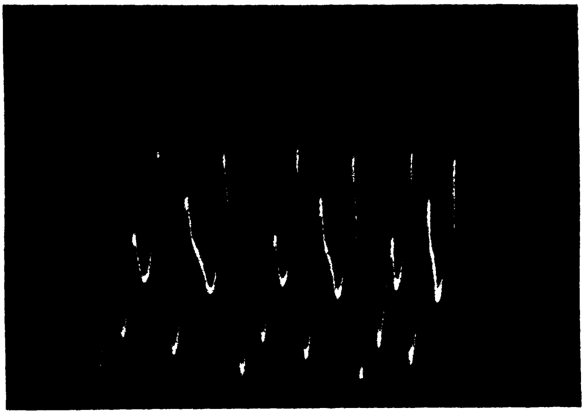


FIG. 147A.—Three cycles of acoustic output from reed trumpet.

Pickups employed as engine indicators are designed to screw into the standard sparking plug orifice. When a special opening is not provided in the cylinder or head, a short steel tube having a bore of about 0·04 in. and fitted with an adaptor can usually be brazed or welded into the base of a sparking plug.

1. ACOUSTIC PRESSURES. The recording of sound waves, which consist of fluctuating pressures, involves relatively simple apparatus and straightforward methods. It is carried out for one of two main purposes : (*a*) music or speech investigations, such as those concerned with the production of tone colour or the design of auditoria, or (*b*) testing

and research work concerned with noise and vibration in heavy as well as light engineering.

(*a*) An example of an acoustic oscillogram is shown in Fig. 147A, representing three cycles of the sound from a toy trumpet. In this, a brass reed is caused to vibrate in a closely fitting aperture, and the sound is controlled and amplified by a conical brass horn. A carbon microphone was used to pick up the sound, and was simply connected to the input terminals of the oscillograph. There are a number of methods whereby such a wave can be resolved into its components. In general, the first step consists of dividing the length of the cycle into a number of equal parts, such as 12 or 24, depending on the complexity of the wave. The amplitude of the curve at the successive points is measured along ordinates drawn through them, and the analysis is performed by substituting these values in a formula. There are several of the latter given in physics text-books,* all of which afford a simplified method of multiple integration, and thus carrying out the requirements of the Fourier equation. In the present case the relative strengths of the first eleven harmonics were found to be 4, 9, 6, 5, 9, 11, 2, 22, 11, 8, 10.

Two examples follow of investigations in which the results were obtained by straightforward scrutiny of the oscillograms. Both illustrate the light that modern oscillography is able to shed upon vexed musical problems.

The first was a careful series of tests to ascertain whether the finger of the pianist did actually exert any influence upon the tone produced by the string, apart from obvious changes in volume and quality due to variation in the applied force. Trains of waves originating from the striking of a given key by a skilful pianist were first recorded, and an exactly similar set was then generated by the dropping of a weight upon the key from various heights. It was proved that the two sets of waves corresponding to a given mechanical pressure were absolutely identical, and that therefore the fingers of the player cannot influence the quality apart from the intensity of the sound.† Charm of execution hence can only depend on the even striking of the notes by the various fingers whether they are played in succession or simultaneously, on correct judgment as to the power used for any note or chord, and on the period during which the dampers are depressed.

The second investigation was carried out to settle whether violins constructed by the " old masters " did actually produce a better tone than good modern products. In this case the oscillograph investigation was conducted in parallel with personal tests, an audience of educated listeners, who were kept in ignorance as to the identity of the instruments being played, recording their impressions as to the respective tone qualities. Both science and art gave the same decision, namely that the tone quality of the modern instrument was at least as good as that of the old ones. At the same time the effects of varnish and other structural details were analysed, and valuable information secured. It was proved, for example, that there is no mysterious virtue in the varnish employed by the old masters.* A recent personal test organised by the British Broadcasting Corporation, and judged by " wireless " listeners, incidentally reached the same conclusion as to the quality of old and new violins.†

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* E.g., Watson, " A Text-Book of Practical Physics," Chap. I. (Longmans).

† See Sir J. Jeans, *Science and Music* (Cambridge), p. 98.

The acoustic properties of an auditorium were largely a matter of trial and error until quite recent years ; but the perfection of sound measuring and recording equipment has led to a much better understanding of the problem. Tests on the natural frequency and the damping of an enclosure are carried out by setting the space in vibration and recording the resultant sound oscillations by means of a microphone and cathode oscillograph. The exciting cause may be a spark discharge from a condenser.

Echo production by sounds of various frequencies is studied by means of a loud speaker actuated by an adjustable sound generator, controlled by a double-circuit switch that simultaneously cuts off the sound and starts the single-sweep of the oscillograph. If the sweep is exponential, and its time-constant is made equal to that of the echo, the envelope of the oscillogram will be a triangle with straight sides and not a paraboloid, and this principle may be used for a quick determination.

(*b*) The study of noise and that of vibration have much in common, and are carried out by very much the same kind of apparatus. Information that is required, in order to eradicate the causes of either, includes its intensity under various conditions, its frequency or frequencies, and its variation with angular velocity or pressure. All these can be readily shown on the oscillograph screen.

An example is the amplitude of vibration of rotating shafts, a method for recording which was devised by J. A. Mitchell,‡ in connection with an investigation on the critical speeds of centrifugal pump shafts. A small vertical piston was arranged to slide in a guide cylinder supported by a cantilever in such a position that the end of the piston-rod rested upon the shaft. The upper end of the piston was in contact with a resistance-type pick-up similar to that described later on p. 167

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* See *Journal of the Franklin Institute*, January, 1940, p. 1.

† See *Radio Times*, August 15th, 1941, p. 4.

‡ See *J. Sci. Insts.*, August, 1943, p. 134.

and shown in Figs. 150 and 151, and the variations of current in the pick-up circuit due to its varying resistance were recorded by the oscillograph.

Calibration of the record was effected by sliding an eccentric sleeve, giving a throw of 0·02 in., along the shaft and under the piston, and then running the shaft at a speed where its own vibrations were negligible.

Noise is very similar to vibration, and is in fact the direct result of vibration within audio-frequency range. It has been pointed out by J. S. Forrest * that the noise given out by static equipment, such as transformers and reactors, does not contain many components, these being chiefly the lower harmonics of twice the mains frequency. For recording such waves the cathode oscillograph is very suitable.

The microphone is located at the various desired points, and connected in the usual way to the oscillograph through an amplifier of sufficient voltage gain ; 100,000 was required for the tests in question, using a crystal microphone. Two methods are available for showing the results. A linear time-base may be employed, and the components analysed from the resultant record ; or a Lissajous' figure may be obtained by energising the horizontal deflectors from the supply circuit. The latter method usually enables the chief components to be readily identified, and their phase relationships to be estimated as in Figs. 65 and 71.

**Piezo-electric Pickup.** Probably the most direct conversion is afforded by means of the piezo-electric effect.† Certain crystals, such as quartz and tourmaline, have the property of developing an electric charge between two opposing faces when positive or negative pressure is applied to them. In the absence of any leakage, this charge produces a potential difference which in the case of quartz varies linearly with the applied force. When, therefore, the two faces are connected to a thermionic valve having a very high grid/filament resistance, such as an Osram " electrometer " triode ($10^{15}$ ohms) or an appropriate double-grid valve, in either case forming the input element of an amplifier, a sensitive and dead-beat method is provided of tracing even the most impulsive pressure fluctuations.

There are two ways of applying the pressure to the crystal. First, a lamination may be cut perpendicular to the " electrical " axis, and the pressure then applied to the broad faces. A common arrangement is to mount two such laminations " back-to-back " with an electrical connection brought out from between them, and the outer faces connected together and earthed. The pressure to be measured would then be applied to these faces. Secondly, a more or less cubical shape might be adopted, and the pressure applied to faces perpendicular to those used above. This would cause a negative pressure along the electrical axis, and negative readings would be the result.

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* See " Applications of the C.R.O. to Electric Power Systems," *J. Sci. Insts.*, May, 1943, p. 69.

† See Appendix D.

2. BOMB PRESSURES. An example of the first method of using the quartz crystal was devised by Webster in the U.S. Naval Research Laboratory * for recording the impulsive pressures developed inside an exploding bomb. A stack of 21 quartz crystals, each 0·69 in. square by 0·053 in. thick, separated by platinum electrodes, were contained in a pure bakelite cartridge having screwed brass ends, the pressure being transmitted to the pile by means of a piston $\frac{3}{8}$ in. in diameter. As maximum values in the vicinity of 30,000 lb. per sq. in. were recorded, this arrangement entailed a maximum load on the crystals of less than one-third the above value, as compared with their crushing strength of about 50,000 lb. per sq. in. The results given were highly satisfactory.

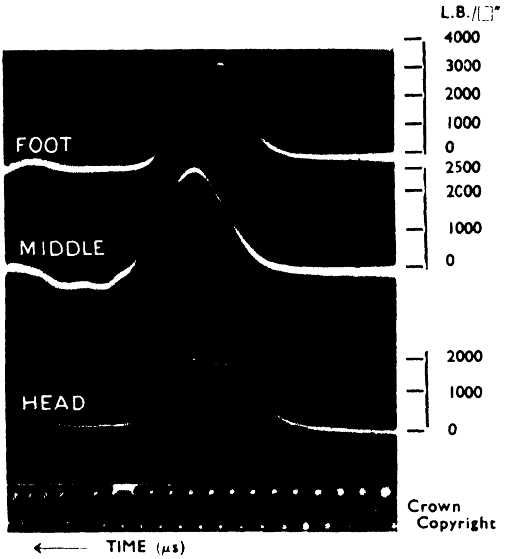

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FIG. 148.—Impulse pressures during driving of ferro-concrete pile, at three positions.

Pressures produced by the explosion of bombs and depth-charges in sea water have been studied in this country by means of a large tourmaline crystal suspended in the water. The cathode oscillogram indicated a pressure pulse closely resembling the voltage surge in

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* See *Journal of the Franklin Institute*, Vol. 211, January, 1931, p. 607

Fig. 12, with a front of 0·1 ms and a " tail " of about 0·4 ms, followed after a long interval by secondary pulses representing reflections from the sea-bottom and the surface. Most important developments in the design of ships' hulls resulted from these tests.*

3. PILE DRIVING IMPULSES. The nature of the stresses created in the head of a concrete pile by the impact of the falling " monkey " has been recorded by means of the second type of piezo detector, which was actually embedded in the concrete during the casting process. In this case the quartz crystal was cut into the form of a rectangular prism, ¾ in. long by ¼ in. square, the end faces of which were perpendicular to the " third " axis, while the long pairs of faces were perpendicular to the optical and electrical axes respectively. The last pair were metallised over most of their surface by means of a film of copper, from which electrical connections were taken to the amplifier. The crystal was housed in a brass tube, its end faces being located on metal pistons, with which the caps stopping the ends of the tube were in contact. Thus the pressures in the concrete were directly applied to the end faces of the crystal.

A typical record is shown in Fig. 148,† indicating the pressure variations in a ferro-concrete pile, 15 ft. × 7 in. × 7 in., due to a blow from a 1,000-lb. drop hammer falling through 12 in. A buffer, interposing a felt pad 1 in. thick, was placed on the head, while the foot was clamped in contact with a rigid concrete foundation. Pickups were cast in the pile at positions 4 in. from each end, and at the middle of the length. The triggering switch of the time base was mounted close to the hammer and its vertical position adjusted so that the descending mass tripped the circuit at the right moment for securing the record.

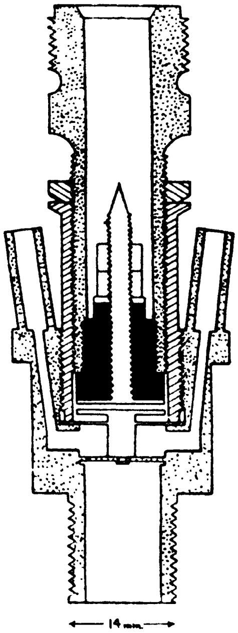

FIG. 149.— Cossor-Dodds condenser type pressure unit.

The leads from the three pickups were taken to a distributing switch, enabling the three oscillograms to be obtained in turn. It will be observed that the curves given by these conditions are smooth, with the maximum compression at the foot equal to about twice that at the head. Following the rebound, tensions are produced at the middle and foot of the pile. When a felt pad was inserted between the foot and the concrete base, a longitudinal vibration occurred, with a frequency of 455 c/s. The observations agreed quite well with previously calculated results, the divergence being only from 7 to 10 per cent.*

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* See Goodall, " Some Recent Technical Developments in Naval Construction," *The Engineer*, Vol. 178, November 17th, 1944, p. 396.

† By permission of the Controller, H.M. Stationery Office. See *Proc. Phys. Soc.*, Vol. 46 (2), March 1st, 1934, p. 196.

**Condenser Pickup.** A good example of the condenser type of pressure unit is that produced by Professor Dodds † and illustrated in Fig. 149. The model shown is suitable for general pressure recording purposes, while its construction renders it suitable for screwing into an engine cylinder. It consists essentially of three concentric tubular parts mutually screwing into one another. The main pressure diaphragm is solid with the outer member, and its thickness is suitable for a definite range of pressures. Several elements would therefore be required for meeting all needs, each having a diaphragm of different thickness.

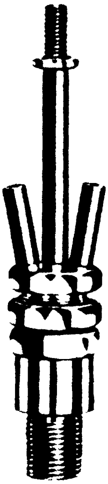

FIG. 150.—Resistance type pressure unit, external view (Cossor).

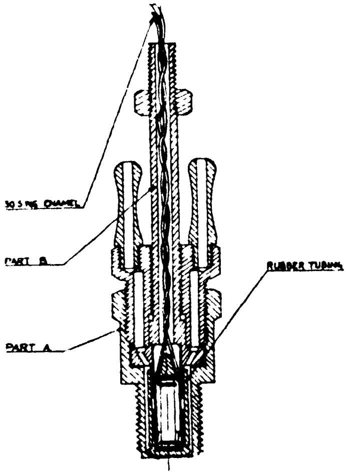

FIG. 151.—Resistance type pressure unit, vertical section (Cossor).

The moving electrode is carried by a stem supported at one end by the centre of this outer diaphragm, and also near the other end by a further diaphragm that is of one piece with the stem itself, and is clamped in position by screwing down the intermediate tube. Finally, the fixed electrode is held by an insulating bush in the inner tube, the height of which can be so adjusted as to provide an air-gap of only one or two thousandths of an inch. Cooling water may be passed between the two diaphragms by way of the two tube connections shown, in order to obviate damage and change of calibration due to heat.

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* See also Glanville, Grime and Davies, "The Behaviour of Reinforced Concrete Piles during Driving," *Journal Inst. C.E.*, December, 1935.

† See *Journal Inst. Automobile Engineers*, November, 1937.

Such a design, while being practically indestructible, is capable of giving sensitive and accurate results. The frequency range is from 150 r.p.m. to the highest speeds used or likely to be used in practice, including a rate of change of pressure equivalent to 30,000 c/s. As the moving electrode is unflexed and thus always moves parallel with the fixed member, the indications vary linearly with the pressure for all values within the elastic limit of the diaphragms.

Since the above pressure unit is a rate-of-change device, it is not capable of measuring a constant unidirectional value, and calibration must therefore be effected dynamically. A Bourdon gauge is connected through a non-return valve to the same source of pressure during an actual run. When its reading has become steady, it measures the maximum peak pressure reached ; and this is then compared with the highest value in the oscillograph record.

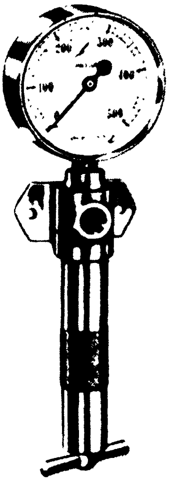


FIG. 152. — Calibrating pump and gauge.

**Carbon Resistance Pickup.** A third type of pressure unit resembles the carbon microphone in that it employs a pressure-sensitive carbon resistance. Outside and sectional elevations of an example designed and made by Messrs. Cossor for use with internal combustion engines are given in Figs. 150 and 151. The diaphragm is a light one, its function being to compress the resistance through a piece of metal interposed for damping and stiffening purposes. This device, unlike the condenser type, can be calibrated statically, and a special gauge shown in Fig. 152, fitted with a compressor of the " grease gun " pattern, is provided for the purpose. To use it, the compressor piston is screwed in until a desired reading is given by the gauge and the position of the spot is marked on the oscillograph screen by means of a grease pencil. The process is repeated for suitable increments of pressure, to provide a complete vertical scale marking. As the resistivity of the carbon varies considerably with temperature, the cooling jacket is of especial importance.

**Induction Pickup.** An induction type of pressure converter is used in the Standard-Sunbury engine indicator. Its general appearance and design are shown in Fig. 153 and resemble the condenser type ; but its principle is that of the inductor alternator, and is the exact converse of the telephone receiver. The silicon-iron diaphragm has a thickness of about 0·03 in., and is clamped before one pole of a strong permanent magnet, round which a coil is wound. Movement of the diaphragm induces voltages in the coil, which are suitably amplified.

Water-cooling of the pickup is obviated by leading the gas pressure to the diaphragm through a small passage about 1 in. long in the metal of the body. It should be remarked that the effect of a short connection of this kind is to delay the arrival of the pressure changes by a period due to the velocity of sound, *i.e.*, about 100 $\mu$s in the present instance. In the rare cases where the effect is of importance, a correction can be readily made on the above basis. The induction type possesses the advantages that its inertia is a minimum, and its accuracy is not likely to be impaired by traces of moisture or by variations of temperature.

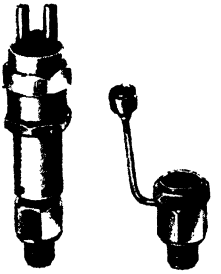
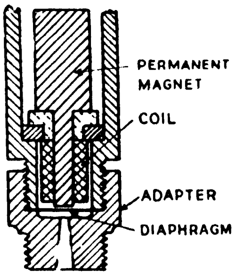


FIG. 153. — Induction type pickup (Standard Sunbury). Left, external view ; centre, calibrating adapter (tube goes to external air reservoir with gauge, adapter contains non-return valve) ; right, section view of pickup.



**Strain Gauge Pickup.** A somewhat different requirement is met with in the measurement of elongation in solids, such as plates, bars and rods forming parts of structures and vessels. The close design of buildings, bridges, ships and aircraft has in the past been greatly restricted by inability to determine the exact proportion of the total stress that is taken by the various members under practical conditions, and large " factors of ignorance " have to be employed to secure the necessary margin of safety. But the urgent necessity of ascertaining the stresses in all the members of an aeroplane structure led about seven years ago to the development of strain gauges, which have enabled factors of safety to be reduced and the weight to be kept down much more nearly to the minimum safe value.

Strain gauges consist in principle of a " grid " of fine resistance wire attached to the member under test before the stress is applied. The direct effect of a positive strain is to increase the length of the wire and reduce its cross-section, both of which raise the value of its resistance ;

but it is found in practice that the variation in resistance is somewhat greater than that indicated by change of dimensions alone, *e.g.* the "strain sensitivity" for a given material may be 2·05 instead of 1·7; and the exact figure is found by test for each type of gauge. Then if due attention is paid to the support of the wire, not only is the strain sensitivity reasonably constant for many cycles of stress variation and for a wide range of stress, but it is of the same value for compression as for tension, and the indications are reliable even for strains that exceed the elastic limit.

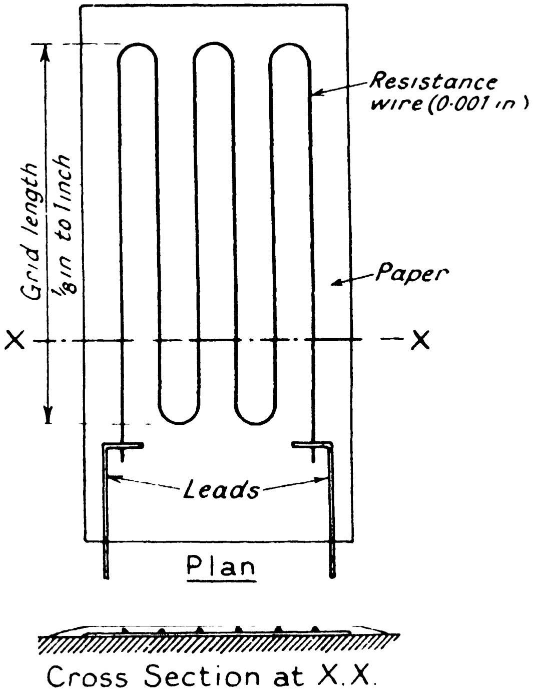


FIG. 153A. Typical strain gauge.

The construction of a strain gauge is simple, as indicated in Fig. 153A. A diameter of about ·001 in. is usual for the wire, and it is held in place throughout its length by a layer of elastic cement, generally upon a paper backing. The whole is then cemented upon the surface of the member under test, with the length of the wires parallel to the direction of the stress. Care must be taken that the lead-in wires do not bear any of the stress.

The gauge is included in one arm of a bridge circuit, and the effect of temperature variation is balanced by including a similar gauge mounted on unstressed metal in the other arm. It is not satisfactory to employ a single gauge composed of so-called zero-coefficient wire, as it is very difficult to secure a metal with a resistance/temperature coefficient sufficiently near to zero for accurate results. Electronic recording apparatus is used even for static tests in order to secure adequate overall sensitivity.

The chief advantages of this form of pickup are cheapness, lightness, small dimensions (the usual length of the " grid " is only from $\frac{1}{8}$ in. to 1 in.), accuracy, and suitability for rapidly alternating stresses. For example, it has been successfully used to record the stress fluctuations in the leg of a tuning fork, as well as the behaviour of metals under impact. A further application for which it has been ideally suited is the measurement of internal stresses in sheets due to welding operations.

4. ENGINE INDICATORS. The electronic indicator for steam or internal combustion engines affords an interesting example of the recording of high-frequency cyclical pressure fluctuations. In order to measure the power input to the cylinder and to check the setting of the valves, a graph is required connecting the cylinder pressure at any instant with the position of the piston or crank. The standard mechanical indicator is an expensive little instrument consisting of a small vertical cylinder which is designed to screw into an orifice in the wall of the engine cylinder or cover, and is fitted with a light piston and piston-rod. A straight-line motion is interposed between the rod and a stylus, which thus accurately records the movements of the indicator piston, suitably magnified, upon a chart clipped to a small drum revolving through a limited angle about a vertical axis.

In order to provide the horizontal movement or time-base, it is necessary to rotate the drum in synchronism with the movements of the engine piston, and this is accomplished by means of a special lever mounted on the engine, the end of which is linked to the piston by a connecting-rod. A string is fixed at a suitable point nearer the fulcrum and is taken to a pulley at the base of the drum, which possesses an internal spiral-spring to keep the string tight.

Accuracy can only be obtained with this instrument if the friction and inertia of the moving parts are cut down to the absolute minimum. Although the requirements have been satisfactorily overcome for the reciprocating steam engine, all the difficulties have been greatly increased in the case of the internal combustion motor, for which a diaphragm of the " aneroid barometer " type, with mirror magnification, was adopted in place of the indicator cylinder and piston. Even this modification does not afford a sufficient improvement for high-speed automobile and aero engines ; while the increase in cylinder-head clearance involved by either device may be serious for compression-ignition engines. In addition, the link-and-lever system for providing the horizontal travel is usually expensive and troublesome to install.

All these difficulties are reduced to small proportions by the electronic engine indicator. The pressure fluctuations are converted into a varying voltage by one of the devices already mentioned, and the output is passed through a valve-amplifier to one pair of oscillograph plates. For the horizontal travel, a photo-electric arrangement can be used to register the piston position, or a time-base synchronised with the shaft rotation may be substituted. In the latter case the cylinder pressures are associated with the position of the crank instead of the piston. As the problems involved and the methods adopted for their solution form especially interesting examples of this branch of oscillography, typical arrangements will be described in some detail.

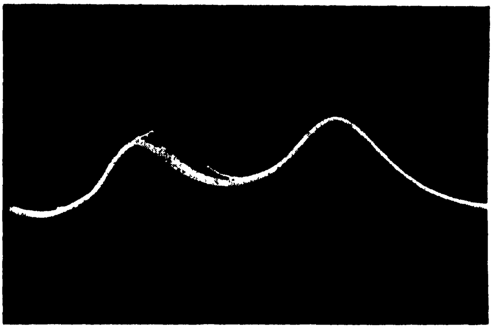


FIG. 154.—Indicator diagram, taken by means of a linear time base.

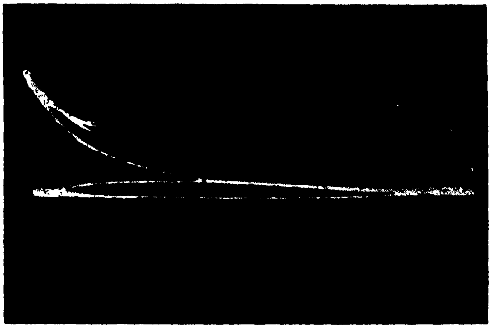


FIG. 155.—Indicator diagram corresponding to Fig. 128, but taken by means of a reciprocating base.

Pickups, or pressure units, based on the carbon resistance, variable capacity, and variable inductance principles, and specially designed for engine indication, have already been described on pp. 166–8 and illustrated in Figs. 149, 150 and 153 ; but the piezo type of pickup is used abroad, typically consisting of two quartz laminations mounted in a holder resembling a sparking plug both in size and general design, the lead being taken from the electrode between them through the insulated stem. Leakage of the electric charge is negligible for all speeds above about 1,000 r.p.m., and there is no upward limit of speed beyond which the results are in any way unsatisfactory. Since it is just in this range that the mechanical indicator fails, the piezo unit was able to fulfil a definite need.

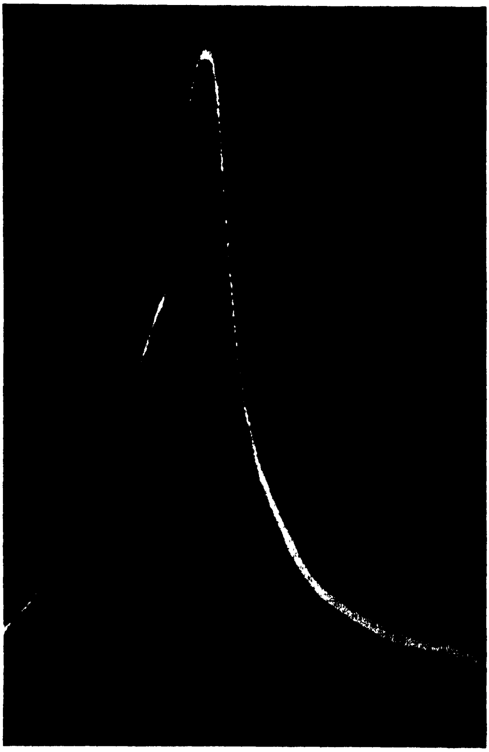


FIG. 156.—Portion of complete cycle from Junkers two-stroke solid-injection Diesel, amplified to show detail of peak ; " pinking " would be shown by oscillation at the crest.

The horizontal travel of the record is most easily provided by a linear time base, synchronised with the engine rotation by means of a tripping contact fixed to a convenient part of the shaft or of the reciprocating system. Diagrams traced in this way would show the fluctuations of pressure, during either one or two complete revolutions, set out continuously from left to right (or *vice versâ*) without reference to piston movement, as in the example forming Fig. 154. Such a diagram is convenient in some respects, but it possesses several minor drawbacks.

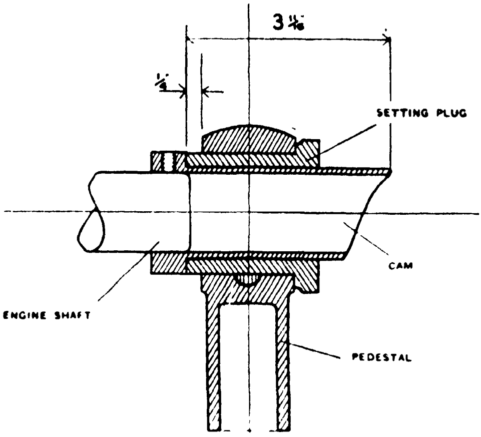


FIG. 157.—Section of cylindrical cam shutter, for operating reciprocating base.

First, mechanical engineers are accustomed to the type of diagram shown in Fig. 155, in which the graph of pressure moves backwards and forwards with the piston travel. This is the form traced by the standard mechanical indicator.

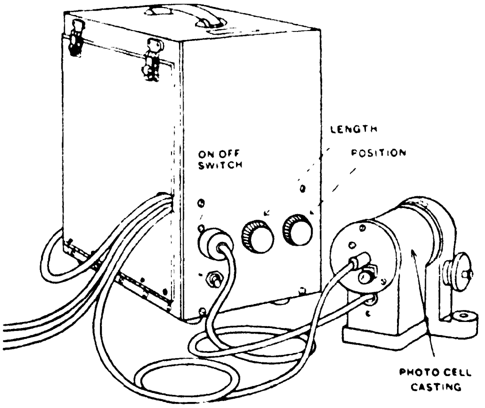


FIG. 158.—Reciprocating-base apparatus (Cossor).

Secondly, the whole cycle will not be shown, as a certain small period will be required for the " fly-back."

Thirdly, the time-base method only approximately represents a crank-angle scale, since it assumes the shaft speed to be constant, which is not the case.

A piston-displacement device has therefore been evolved by Messrs. Cossor, which links up the pressure indication with the piston position at every point, without requiring the old-time mechanical lever gear built on to the engine. In it, the horizontal travel is governed by a photo-cell,* actuated by a beam of light that is more or less intercepted by a cylindrical cam mounted on the engine shaft as shown in Fig. 157. No very elaborate geometry is required to draw out this

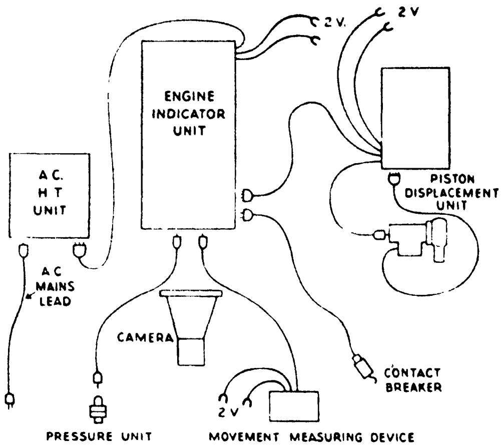


FIG. 159.—Inter-connection of engine indicator components (Cossor).

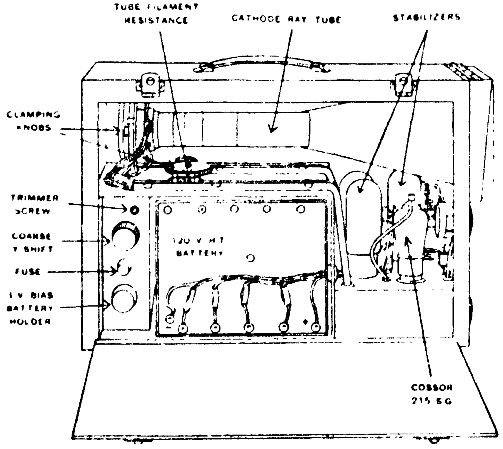


FIG. 160.—Oscillograph unit for engine indicator (Cossor).

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* See Appendix B.

cam in order that the strength of the beam passing it shall be accurately proportional to the piston-travel at any instant. Both cam and photo-cell are contained in a compact and self-contained unit, which is easily attached to the engine, and is shown in the lower right-hand corner of Fig. 158. It is connected by flexible leads, 3 ft. in length, to the control box, which is also seen in the figure, and which provides space for the photo-cell unit and leads during transit.

A general view of all the component units and the way in which they are connected together is given in Fig. 159. The largest item is the oscillograph, or " Engine Indicator Unit," which is shown separately in Fig. 160. To the right of this are the piston displacement unit, already described, and the contact breaker for " triggering " the time base. The last two are, of course, alternatives to each other, and only the one appropriate for the desired type of diagram (as exemplified in Figs. 155 and 154 respectively) would be connected.

Below the oscillograph in Fig. 159 are two more connections which again lead to alternative measuring units. On the left is the pressure pickup, and on the right a " Movement Measurement Device," whereby the operation of any desired part of an engine or apparatus, such as a valve-tappet, can be recorded against time or piston travel by means of a photo-electric cell. The high-tension A.C. supply unit is on the left ; but if A.C. mains are not available, a 12-volt accumulator or an anode converter working off D.C. mains may be used to provide the necessary power.

A special advantage of the cathode-ray indicator is the possibility of selecting and enlarging a portion of the record which it is desired to examine more minutely. An example is shown in Fig. 156, in which the peak pressure wave form has been magnified. It is at this point that " pinking " occurs, and when present is evidenced by a high-frequency oscillation at the peak.

There only remain to be described the oscillograph itself and the camera. The example of the former illustrated in Fig. 160 is designed for use with the carbon resistance type of pickup, requiring only a single amplifying valve, the other three bulbs being neon stabilisers for maintaining the H.V. as constant as possible. The cathode tube occupies the upper part of the case, and is a gas-focussed model. For visual indication, the " red " fluorescent screen having a long afterglow is at an advantage, more especially for relatively slow speeds. When the maximum sensitivity is required for photographic recording, the " blue " screen should be used. Two H.V. batteries, arranged back to back, are provided for the purpose of giving a smooth voltage across the pressure unit.

The camera, shown in Fig. 161, is a simple fixed focus apparatus, the open (right hand) end of which is slid into grooves on opposite sides of the oscillograph screen. An anastigmat lens with an aperture of f/2·8, and a diaphragm shutter giving speeds up to $\frac{1}{250}$ sec., are situated in the interior of the box, and a film- or plate-holder closes the left-hand end. By suitable adjustment of the shutter speed and the lens aperture it is possible to photograph a single cycle. Panchromatic emulsions should be employed if the screen employed gives a red colour. A complete set-up of apparatus for engine-testing, including the oil-engine itself, is shown in the Frontispiece.

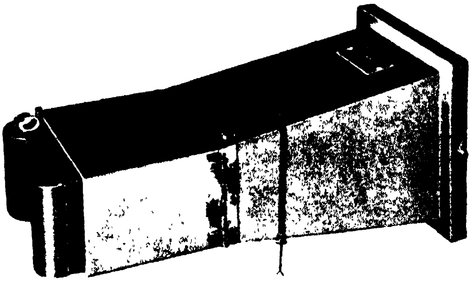

FIG. 161.—Camera for cathode oscillograph, having roll holder for 3¼ in. × 2¼ in. film, f 2·8 lens and diaphragm shutter (Cossor).

5. OTHER APPLICATIONS. The applications of the cathode oscillograph for the recording of fluctuating pressures that have been described above have been purposely selected to represent exacting and widely diverging conditions. Many other industrial and technical applications may be suggested and provided for on the same principles as have been set forth. Examples that have already made valuable contributions to engineering knowledge are investigations into the cutting pressures of machine tools, impact stresses of steel wire, hammer-blows on railway track joints, and starting torques of electric motors ; and the future will undoubtedly see a wide extension of the list.

## CHAPTER ELEVEN

# THE ELECTRON MICROSCOPE

It was pointed out in the first chapter that the cathode ray oscillograph owes its success to the replacement of visible light by an invisible radiation which is able to introduce an important property not previously available, namely that of being directly deflected by electric or magnetic means. Further, it resembles light in that it can be refracted and hence focussed by means of a lens system ; although the latter is composed, not of glass elements but of an electric or magnetic flux, which may be produced in several different ways. Thus a complete projecting system is built up, whereby the image of the spot is focussed brightly and sharply upon the screen or photographic film.

These properties are obviously available for the improvement of other optical apparatus, provided the cathode rays do not possess vital limitations in other respects. Now their most important deficiency as compared with light is the inability of the electron stream to penetrate any material of usual thickness ; a feature which experience with the Lenard window has exemplified. Any object to be treated as a " slide," therefore, must be extremely thin.

With this reservation, the cathode oscillograph needs little adaptation to function after the fashion of a photographic enlarger, or actually as a projecting microscope ; for it is evident that since the human eye is not sensitive to cathode rays, any image can only be viewed through the medium of a fluorescent screen. There is, however, no novelty in the use of projection with a microscope, as it has always been a fully practical alternative for the usual method of viewing, and is essential for obtaining photographic records of micrographs.

It is important that the meaning of useful magnification be realised at the outset. As any student of optics will easily realise, there is no limit to the physical enlargement that can be obtained either by the use of lenses or of projection ; but its utility ceases when no additional details are made visible. In other words, there is no gain in magnifying a blur. The useful power of an enlarging scheme is its ability to resolve two adjacent particles, that is, to render them visible as two distinct entities.

Now the limitation to the resolving power of any microscope is the wave-length of the rays whereby it is operated ; for no detail can be distinguished individually which is much smaller than this value. It is well known that the image of a point as seen through a lens system consists of a disc surrounded by diffraction rings, the proportions of which depend upon the wavelength of the light which is being transmitted ; a fact which is familiar to users of diffraction gratings, astronomical telescopes and similar optical devices. When the object is large in comparison with the light wave, the effect is inappreciable or unimportant ; but it can easily be shown, if the rings be sketched in, that two adjacent points cannot be perceived as distinct entities when their separation is less than about half the wavelength. Thus however much the image of such a pair be enlarged, they cannot be seen as two points if they are nearer together than the above critical distance. Consequently, when visible light of the shortest wave-length is used, viz., blue, with a wave-length of 0·4 micron, the smallest length that can be perceived is 0·2 micron. Taking the resolving power of the normal " naked " eye to be 0·02 cm. (200 microns), the limiting useful magnification is therefore 1,000 diameters, or 2,000 diameters if the utmost power be extracted by oblique vision ; though by employing the invisible ultra-violet rays, a 50 per cent. improvement to 3,000 diameters is achieved. Further *enlargement* could, of course, be effected, but no additional detail could be secured thereby.

Cathode rays possess the great advantage that they function with a wave-length which is only from $10^{-4}$ to $10^{-5}$ that of visible light ; the relationship being—

$$\lambda = \sqrt{1\cdot5/V} \times 10^{-3}\,\text{microns}$$

where V is the " accelerating " potential, *i.e.*, the anode voltage applied to the tube. The further limit ($10^{-5}$) given above thus applies at a voltage of 60 kV, which is about that most frequently adopted. There is therefore scope for a literally enormous increase in useful magnification, and it may be said at once that a value of 150,000 diameters has already been achieved, or 75 times the power of the light microscope. As there are many mysteries waiting to be solved which are of almost vital importance to the human race, and which only require increased magnification to reveal them, it would seem that epoch-making results may be expected from this new development in the very near future.

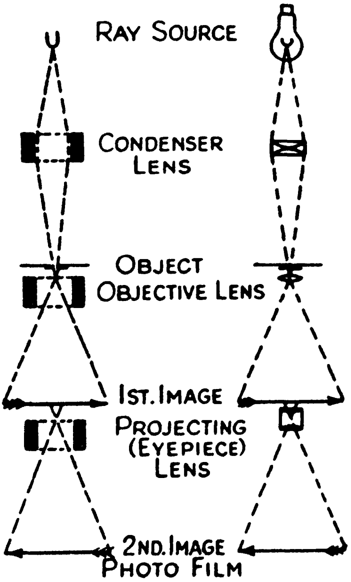

FIG. 162.--Comparison of optical (right) and electron (left) microscopes.

**Principle of Microscope.** There

is very little difference in principle between an ordinary microscope used for projection and a " magic " lantern, except in size ; in fact, only the substitution of a special lens is needed to enable microscope slides to be shown on a 6-ft. (or larger) screen. The usual attachment to a microscope for securing photographic records consists of a bellows camera with a velvet or other flexible tube to fit over the eye-piece instead of the usual lens ; and the magnified image may be viewed in the ground glass screen, provided the room be darkened, just about as effectively as by applying the eye directly to the eye-piece.

The above arrangement is also very similar to that of the cathode ray tube, the chief difference being that the lens system of the latter needs some elaboration in order to project an enlarged image instead of a spot. Actually, the electron microscope in its most effective form has been evolved by reproducing the various parts of the projecting microscope, but suitably modified to deal with cathode rays, as indicated in Fig. 162.

Starting from the light source, the lenses in a standard microscope are, first a " sub-stage " condenser, for collecting a wide bundle of rays from the illuminant and concentrating them through the object into the second, or objective lens, at the lower end of the sliding tube ; and there is finally an eyepiece which magnifies the image formed by the objective and projects it upon the screen or film. These three lenses are employed in their " electron " form in the new instrument, in which they have the same functions and the same relative positions ; the chief difference being that they follow the example of the vertical photographic enlarger and the metal cathode ray tube in being inverted, the source of the rays being at the top and the screen at the bottom.

**Electron Lenses.** As moving electrons possess both electrostatic and electromagnetic properties, they are deflected by both kinds of field. Hence any electrical or magnetic field having axial symmetry will function as a lens. As described in Chapter II, electron lenses are made on both principles ; but it is the electromagnetic type which has been adopted in the most advanced microscopes and for the highest magnifications.

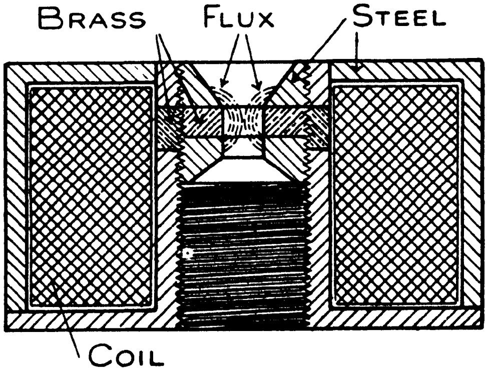

FIG. 163.—Electron lens.

Less ambitious designs, having glass tubes, generally use the electrostatic method of focussing.

The concentrating coil has been the subject of rapid development during the past three or four years. Originally a simple coil, then provided with an external cover or yoke of steel, it is now designed with a very carefully proportioned iron circuit, the object of which is to produce a strong flux of just the desired curvature in the small space occupied by the beam. To achieve this, the iron encloses the coil almost completely, there being usually a gap in the inside cylin-

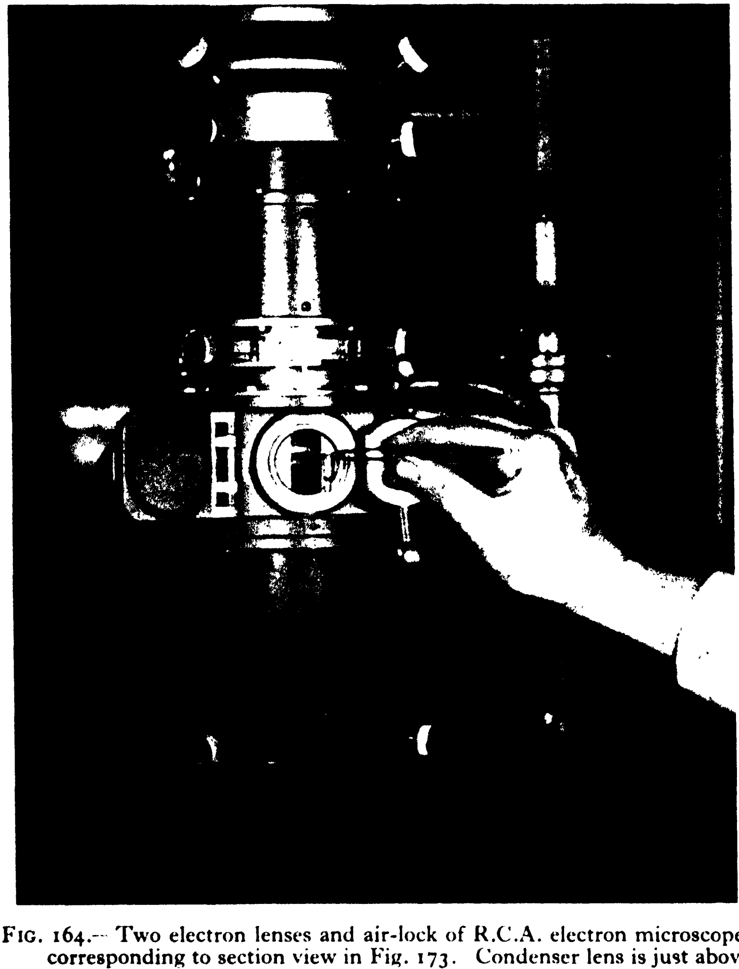

FIG. 164.—Two electron lenses and air-lock of R.C.A. electron microscope, corresponding to section view in Fig. 173. Condenser lens is just above and objective lens immediately below air-lock. Note specimen holder in forceps.

drical portion of only about 0·01 in. The example shown in Fig. 163 illustrates the general form. It is provided with movable pole-pieces, to enable the one * design to serve for the condenser coil, which has the gap in the middle of the bore, and the other two coils, which require the " lens " at the top end. Two lenses in an actual microscope are shown in Fig. 164.

Electron lenses suffer from much the same defects as their glass predecessors, the two chief faults which are limiting progress at the present time being spherical and chromatic aberration. The latter is countered by securing that the cathode stream is as monochromatic as possible, that is, its component electrons must travel at a uniform velocity. Constancy of anode voltage is therefore necessary, in addition to any condition that will reduce collisions or other interference with the electrons.

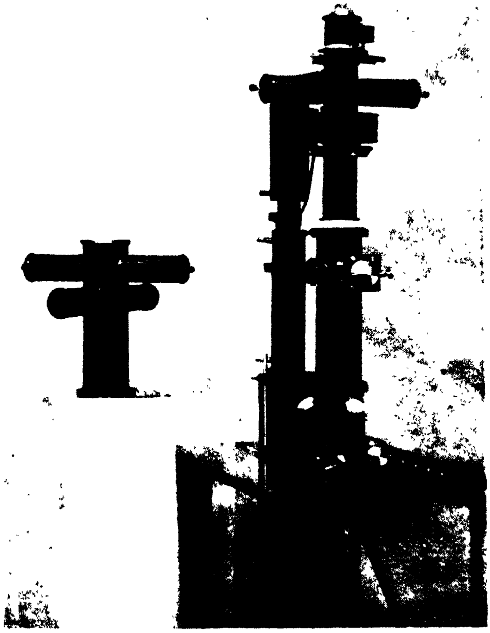

FIG. 165.—Finch electron diffraction camera, with substitute deflection section to convert to cathode ray oscillograph.

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* See Martin, Whelpton and Parnum, *J. Sc. I.*, 1937, Vol. 14, p. 14.

Focussing is effected, as in other cathode ray tubes, by adjusting, not the position of the lenses, but their exciting current, the focal length varying inversely as the square of the ampere-turns and directly as the anode voltage. These relationships again render great constancy essential in H.T. supply and especially in lens current. Messrs. R. C. A. in America have been able to maintain the current for their objective correct to within 0·002 per cent.*

**Electron Diffraction Camera.** Before dealing in greater detail with the electron microscope proper, a less elaborate instrument known as the Electron Diffraction Camera, which is only slightly different from the Cathode Ray Oscillograph, will be described. Like the latter, it only possesses one electron lens, and actually the same structure can be used for both purposes if one section of the main tube be changed.

The external appearance of the instrument designed by Professor Finch and manufactured by the Cambridge Instrument Co. is illustrated in Fig. 165, where the alternative sections for both oscillograph and diffraction camera are shown. If the part standing on a pillar to the left be substituted for the tube section upon the same level, the Cambridge metal-tube oscillograph for recording on flat plates or films will be obtained, corresponding with the rotating drum instrument by the same makers described in Chapter II and shown in Fig. 4.

Internally, the arrangement will also be seen with the aid of Fig. 166 to correspond closely with the description of the typical cathode oscillograph given in the first chapter. The concentrating coil forming the electronic lens surrounds the tube just below the trapping chamber in Fig. 165, and rests on three levelling screws ; but the latter are now of special importance, since they are required to direct the beam at other angles than along the axis. Exposure is here effected by untrapping and retrapping the beam ; but two shutters are provided just above the film, arranged side by side and operated by two turn-buttons outside the enclosure, in order to enable either half of the plate or film to be exposed separately if desired. It should be noted that the photograph shows a somewhat earlier form than the diagram, the trap-plates being omitted in the latter and the shutters being used for all exposures.

Both figures show the construction of the specimen chamber, which is the principal novelty as compared with the oscillograph. This section of the main tube contains the specimen holder, shown separately in Fig. 167, the purpose of which is to support a thin film of the material under examination so that the beam either passes through it, or more usually grazes the surface. In either case the electron stream behaves very much as X-rays do in connection with the investigation of crystal structure, the rays appearing to be reflected at the surfaces of the crystals. Since, however, they penetrate the latter to a very slight though appreciable extent, the resultant pattern is actually due to diffraction. As, moreover, the thickness of material which can be traversed by the usual beam is of the order of $10^{-6}$ cm., the grazing arrangement is much the more convenient, and is the one provided for in the various figures.

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* See *Electrical Engineering*, April, 1940, Vol. 60, p. 161.

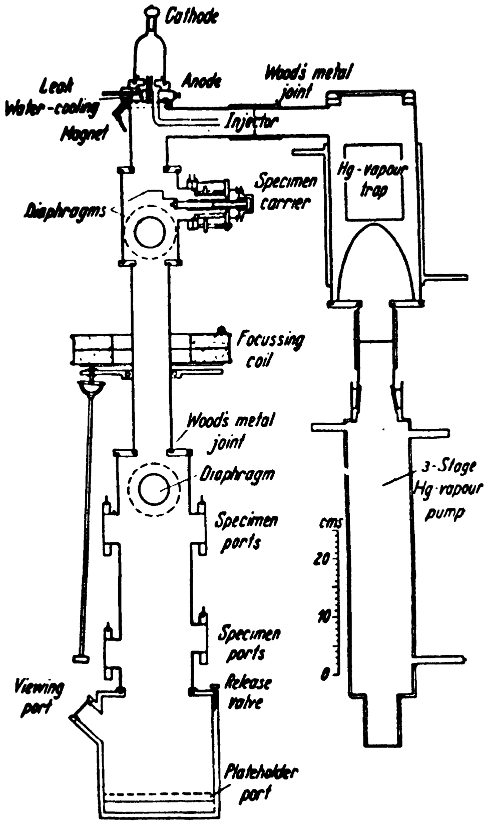

FIG. 166.—Finch diffraction camera ; sectional diagram.

The specimen under investigation is deposited on a flat disc of about 1 in. in diameter, which is seen clipped to the right-hand end of the mount in Fig. 167. By means of a flexible bellows construction and a number of adjusting screws, the position of the film can be varied from outside the tube so as to alter its inclination and its position with respect to the beam, the movements provided comprising rotation as well as axial and transverse displacement. In use, the adjustments of specimen and concentrating coil are operated so that the beam is focussed and impinged upon the surface, and the inclination obtained at which the diffraction rings appear in the screen. The latter is then rotated out of the way, the shutter opened, and the film exposed for a period averaging about 0·2 sec. The power supply is from 0·1 to 0·5 mA at 20 to 70 kV.

The principle of electron diffraction is identical with that of X-ray diffraction ; in each case the arrangement of atoms in the crystal forms a grating or lattice and gives rise to diffraction rings which indicate its constitution. But whereas X-rays are very penetrating, and hence reveal the internal state of the object, the electron stream cannot get through the immediate outside skin, and therefore analyses the condition of the surface. It will be seen that the two methods are not in competition with each other, but are complementary.

The utility of the electron diffraction camera has been enhanced by the great importance of surfaces and films in modern applied physics and chemistry. Photo-cells, thermionic valves, photographic emulsions, artificial silk, surface coverings such as lacquers and varnishes, oils, dusts, films, metal surfaces in relation to polish, wear and corrosion, and many other similar examples, all require for their efficient development an exact knowledge of the surface structure, such as is afforded by the present apparatus.

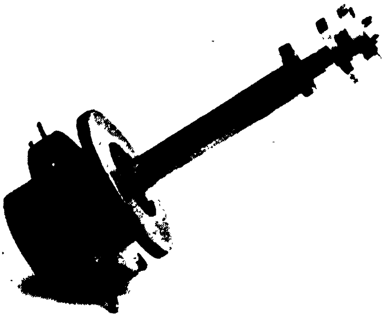

FIG. 167.—Specimen holder for diffraction camera.

When solid materials are examined by transmission instead of reflection, a special transverse holder is fitted instead of that illustrated. A slight modification of the apparatus enables gases to be passed across the beam and to be investigated in a similar manner. Also local heating by means of a small electric arc can be introduced to enable surfaces to be examined at elevated temperatures.

Two representative examples of electron diffraction figures are shown in Figs. 168 and 169. These were taken by Professor Finch, who has been responsible for so much of the pioneer work in connection with the new science. The first is a " transmission " record, obtained by passing the cathode stream through a partially oxidised film of tin-foil. Complete rings are produced which are fine and sharply focussed, enabling the nature of the surface to be accurately deduced. Extremely useful information is being secured by means of similar figures with regard to the growth of oxide coatings and their protective value against further corrosion. It has been found that the first layer to form usually continues the existing crystal formation of the metal instead of adopting that of the oxide itself, a phenomenon known as Basal-plane Pseudomorphism. When this occurs, the oxide is likely to form a much more impervious coating than when there is a discontinuity between it and the metal. Similarly with plated coatings, the absence of a discontinuity would result in better adhesion.

Reflection records are in general not so finely focussed as those obtained by transmission, since the crystals are not all at the same distance from the photographic film. In addition, they cannot extend over quite a complete semicircle. But transmission is only possible for thicknesses not exceeding 0·01 $\mu$ ($10^{-6}$ cm.), and is hence chiefly employed to record the growth of thin films, as in the illustration.

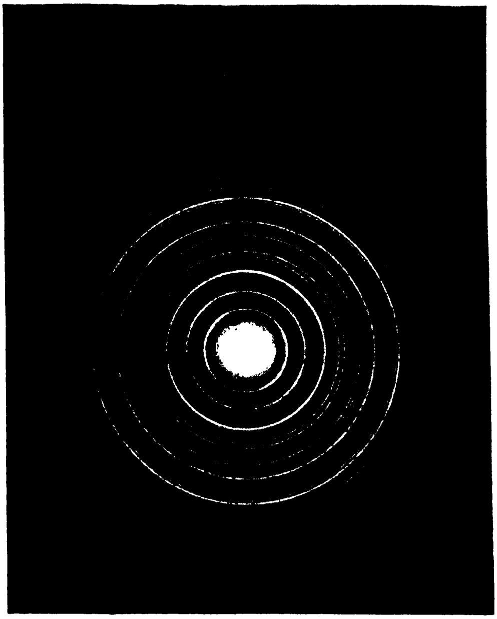

FIG. 168.—Tin foil partially oxidised.

The example of a reflection pattern given in Fig. 169 is of a natural diamond face, and shows the phenomena known as Kikuchi lines, which again reveal the crystalline structure of the surface. They are due to electron scattering within the crystal and subsequent reflection. The record was taken in a direction parallel to a principal crystallographic axis, which accounts for the symmetrical arrangement of the lines.

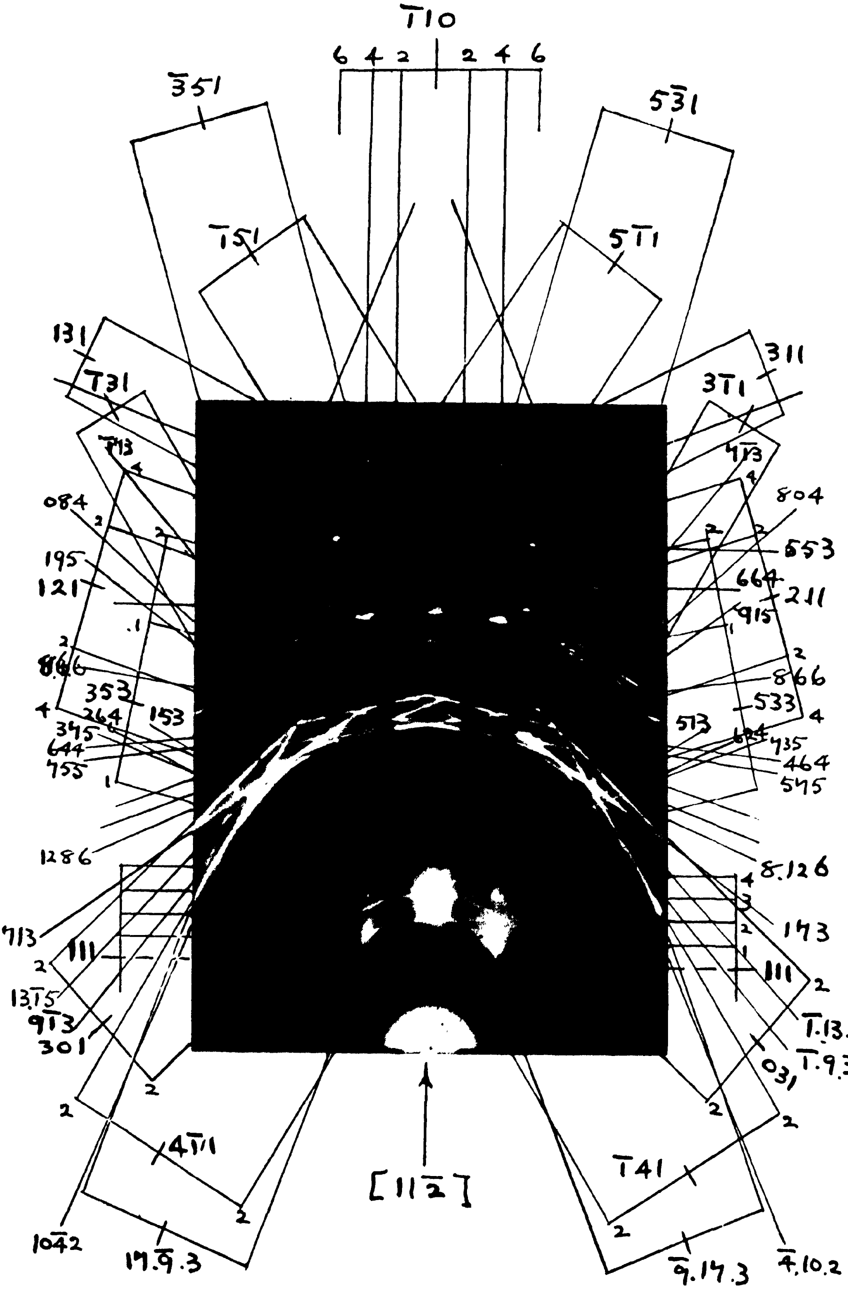

FIG. 169.—" Reflection " pattern from natural diamond.

**M.V. Electron Microscope.** A high magnification electron microscope, which could also be used as a diffraction camera, was designed by Martin, Whelpton and Parnum, and made by the Metro-Vickers Electrical Co. early in 1936. Its general appearance is shown in Fig. 170, and its design is based upon the metal-tube cathode oscillograph by Burch and Whelpton.* Hence it originally possessed a cold cathode to which an accelerating voltage of 20 kV was applied, and stood about 6½ ft. high overall. Like the original form of the tube that has just been described, it was equipped with a beam-trap just below the end of the discharge tube, to enable precise exposures to be made.

Not only was the instrument a complete electron microscope with three lenses, but when first made it also incorporated an optical microscope with a magnification of 200 which was intended to act as a "finder." Like the main instrument, it was placed with its eyepiece downwards, and was viewed by means of a right-angle prism. It can be seen as a small tube on the right-hand side of the large one, and approximately on a level with the objective coil.

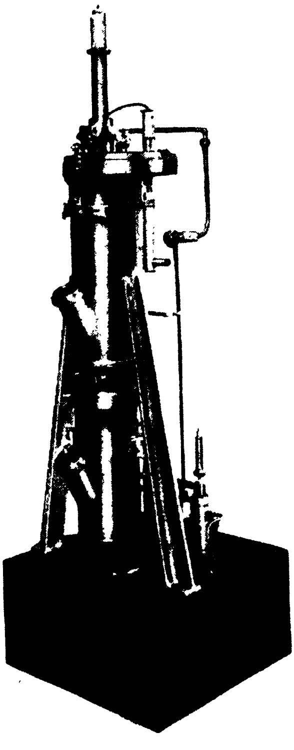

FIG. 170.—M.V. electron microscope.

The two instruments were registered with each other by having the same object carrier plate, which was of circular shape and pivoted about its centre. Two object carriers were located in symmetrical positions 180° apart, and by turning the plate through this angle, an object could be transferred from the optical to the electron microscope or *vice versâ.* Since the object must be inside the vacuum, the whole disc must be situated in an enclosure forming an extension of the main tube ; and this again necessitated the optical microscope being partly above and partly below the enclosure.

The two upper lens coils were mounted immediately above and immediately below the object plate. So close must the objective be to the object that although it was designed as shown in Fig. 163, with the flux concentrated as close to the upper end as possible, a vertical movement was almost essential either to lower the object into the shallow hole above the air-gap, or to raise the lens-coil through the same distance. In the present case, the coil was supported by a sliding mount, the position of which could be adjusted by an external lever. Unlike the concentrating coils of the instruments described previously, therefore, the present objective coil was wholly inside the main tube ; and the condenser and projector (eyepiece) coils were placed similarly, but could be moved laterally in two directions at right angles to each other by external screws. The object carriers consisted of short tubes shaped like truncated cones projecting downwards from the rotating plate, supporting the very small objects mounted upon extremely thin diaphragms at the lower and narrower end.

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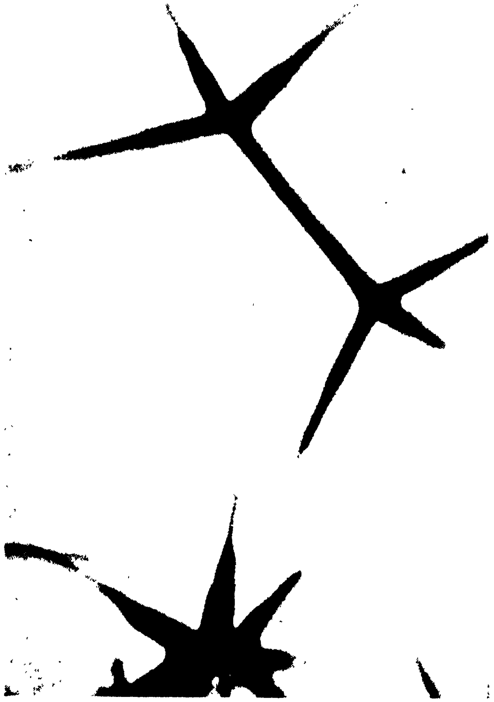
* See Figs. 51 and 52, and p. 66.



× 20,000.

FIG. 171.—Electron micrograph of zinc oxide smoke particle.

There were two fluorescent screens and two cameras, one set being about half-way down the main tube for recording the first image, and the other at the base of the tube for the final image. Separate observation tubes were provided for viewing each as shown.

The instrument described above was in use at the National Physical Laboratory for two or three years. Several changes were made in the original design, the chief consisting of the use of a hot cathode, which rendered the beam more manageable, and the disuse of the optical " finder " microscope.

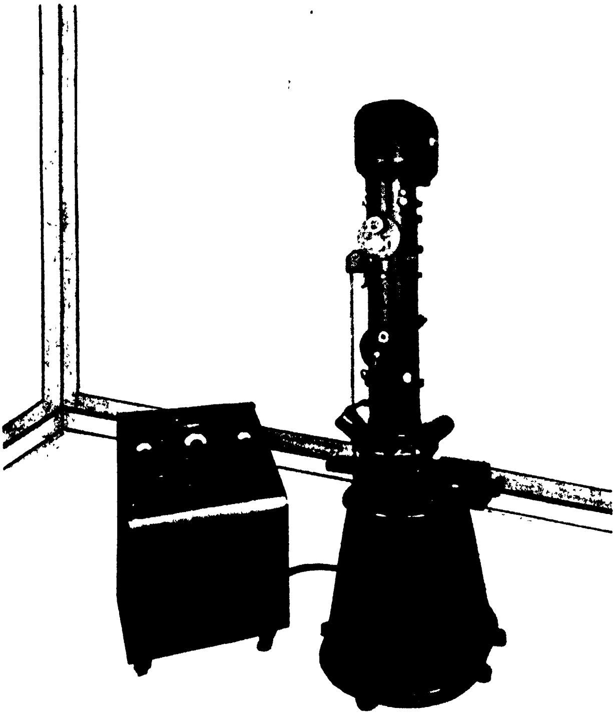


FIG. 171A.—M.V. electron microscope, 1945 model.

Among the investigations that were carried out at the Laboratory with the original instrument, the most notable is probably that dealing with the nature and properties of dusts and smokes. A typical micrograph * is given in Fig. 171, showing a particle of smoke from burning

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* Reproduced by permission of the Director of the N.P.L.

zinc, and portions of other particles, employing a magnification of 20,000. The particle is a crystal or " dendrite " of ZnO, and was prepared by permitting the smoke from the metal, burning in air, to condense on the edge of a small hole in a metallic zinc plate. Under these conditions some of the crystals overhang the hole and are readily photographed.

Wartime conditions prevented work on an improved model until late in 1944, when that shown in Fig. 171A was developed, being one of the first six production models to be completed. A number of refinements were applied, especially to the lens system and the electronic circuits. As a result of much experimental work on the optical arrangements, and the securing of a high degree of constancy in the anode voltage and the lens coil currents, a resolving power of better than $\cdot 005\mu$, implying a useful magnification of about × 50,000, has been attained. The electrical circuits connected with the pumping plant are contained in the base of the instrument, while the oil-immersed 50 kV power supply is in a separate tank, and those parts responsible for the control of the focus, magnification, and other factors are housed in a separate small floor cabinet shown on the left of the figure, the sloping top of which forms a control desk.

The object and photographic plate are introduced by means of air-locks seen in the upper part of the column and at its base respectively, and near the latter are three pairs of viewing ports. Accessibility of all important parts was one of the chief aims of the design. Owing to the difficulties of the times, the model was necessarily an " austerity " one, and was not completed till after the appearance of the R.C.A. instrument, which will therefore be described in greater detail below to exemplify recent progress.

**R.C.A. Electron Microscope.** Successful electron microscopes were also manufactured abroad, two of which were by L. Marton * in Belgium (1934) and by Prebus and Hillier at Toronto University (1938). The latter possessed the same general arrangement as the first M.V. instrument, but the main tube, instead of containing the electron lenses, was divided into separate sections, that made vacuum-tight joints with the lens-flanges. A simpler and more accessible design resulted, possessing also the considerable advantage that only a relatively small compartment had to be opened and re-pumped when a specimen was inserted or removed. A hot cathode was used of hairpin shape, the position of which could be so adjusted in its cathode shield that only the electrons from its extreme tip were employed. Very promising results were given by the instrument, a resolving power of about ·02$\mu$ being obtained.*

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* See *Nature*, Vol. 133, 1934, p. 959.

Shortly after this time, both L. Marton and J. Hillier joined the Staff of the R.C.A. Manufacturing Co. (New Jersey), who first constructed an experimental model to Marton's design, and at the beginning of 1941 placed on the market a finished microscope developed by Zworykin, Hillier and Vance, which has already given magnifications of 150,000 diameters. The first of these was a really practical instrument † giving high magnification up to at least × 20,000 ; and the principal changes effected by the latter designers were in the direction of making it more compact, self-contained, and simple to operate. The advantages of the Toronto model were incorporated and the design given detailed consideration in order to render critical adjustment unnecessary and to facilitate operation ; with the result that it can be effectively used by an average investigator, without any special knowledge of electron physics.‡

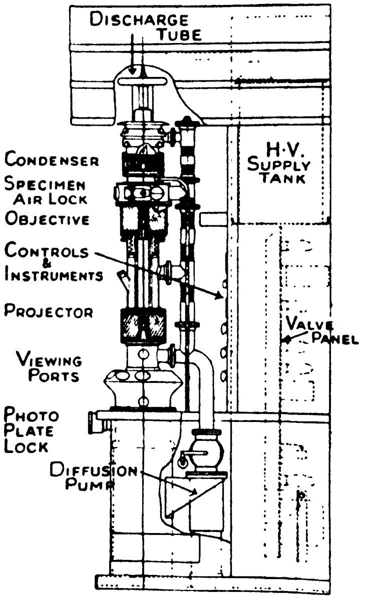

FIG. 172.—R.C.A. electron microscope ; general arrangement.

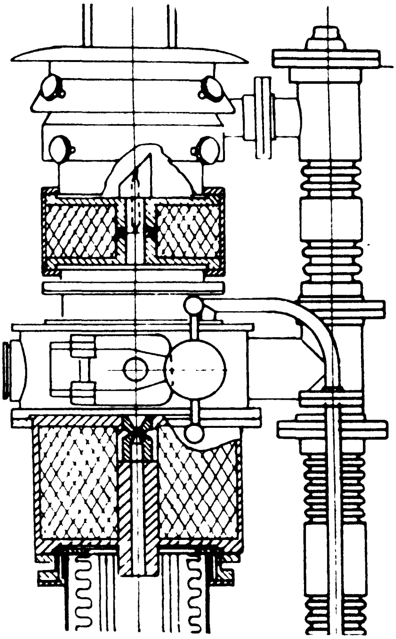

FIG. 173. R.C.A. microscope, details of two lenses and air lock.

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* See " The Construction of a Magnetic Electron Microscope of High Resolving Power," *Canadian Journal of Research*, Vol. 17, April, 1939, p. 49.

† See Zworykin, " Electrons Extend the Range," *Elect. Eng.*, November, 1940, Vol. 59, p. 441.

‡ See Zworykin, Hillier and Vance, " An Electron Microscope for Practical Laboratory Service," *Elect. Eng.*, April, 1940, Vol. 60, p. 157.

In size the R.C.A. microscope is comparable with the two instruments already described and shown in Figs. 165 and 170, and the arrangement of the lenses is similar to that in the M.V. example. Besides the hot cathode and the butt-joint arrangement of tubes and lenses in the Toronto model, an important new feature has been added in the shape of an air lock for rapidly inserting objects into the vacuum. The general arrangement may be seen in the section diagram forming Fig. 172, and details of the tube and coils in Fig. 173.

Although a hot cathode is employed, the anode voltage is in the vicinity of 60 kV, producing a high electron velocity, and thus securing a relatively high degree of penetration. As has been stated previously, all material substances, even including gases, are able to stop or absorb cathode rays ; and this greatly restricts the thickness of the objects which can be viewed by the electron microscope. For some types of object, such as dusts, powders and smokes, lack of penetration may not be very disadvantageous when the contours provide all the information required ; but for most specimens, details of the internal structure, or of the variation in thickness over the area viewed, are important. The voltage stated gives good results for general purposes, enabling, for example, the body-structure of most disease germs to be seen. In special cases where it is necessary to see through specimens of greater thickness than usual, higher anode voltages can be used, in a suitably designed microscope. One such model, employing voltages up to 300 kV, was recently described,* and its increased penetration demonstrated by means of actual examples.

The general design follows cathode oscillograph practice, but the arrangement has been adapted to enable an operator seated in front of the viewing ports and the plate-trap to control the whole instrument. All high voltage supply apparatus, such as coil, rectifiers and filters, are contained in the enclosed oil-tank mounted in the upper part of the cubicle at the back of the tubes. The great advantage of employing " monochromatic " radiation has already been stressed, and this and other advantages are secured by generating the power at radio-frequency (actually 32 kc/s) instead of the usual mains frequency. Smoothing, filtering and screening are all greatly facilitated by the change, and greater compactness obtained.

The valves and other electronic gear are situated on a panel below the tank, while indicating instruments and control knobs are mounted upon the front of the cubicle, where they are within convenient range of the operator. Evacuating equipment, comprising a three-stage oil diffusion pump and mechanical " backing " pumps, is housed under the bench top.

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* See Zworykin, Hillier and Vance, " A Preliminary Report on the Development of a 300 kV Magnetic Electron Microscope," *Journal of Applied Physics*, Vol. 12, October, 1941, p. 738.

As has been already stated, the " lenses " form integral parts of the structure, the tube sections occupying the gaps between these and making gastight joints with the steel enclosures of the windings. Since the tube is discontinuous, the various sections are connected to the pumps by means of a bus-pipe or manifold. All joints have either been made permanent by means of soldering or brazing, or demountable by means of neoprene (synthetic rubber) packing ; it having been found possible to obviate greased joints altogether.

Most interest attaches to the second and fourth sections from the top, which contain the air-locks for the insertion of the object and the photographic plate respectively. These effect a great saving of time through enabling the changes to be made without releasing the vacuum in the whole apparatus. Two handles operate the upper lock, of which the first raises the object from its place just above the objective and closes the main chamber behind it ; whereupon the second admits air to the lock chamber and then opens it to the atmosphere. For the reverse operation, the latter handle closes the outer gate and then connects the lock chamber with the special backing pump for the two locks.

Similar arrangements are fitted for the photographic chamber. Glass plates are used, 10 in. long by 2 in. wide, upon which a succession of exposures can be made. Modern fine-grain technique enables a magnification of up to about 10 times to be effected by enlargement from the negative, thus taking advantage of the fine detail provided by the high resolving power of the electron image. It is good practice to secure as much of the total magnification in this way as possible. Exposure is carried out by using the fluorescent screen as a shutter.

Photographic recording is, however, not needed for every investigation, and six viewing ports are provided for the final image, in addition to two for the intermediate stage.

A revised model, shown in Fig. 174, has recently been produced, in which a number of simplifications and improvements have been effected. The more convenient position of the instrument and control panel will be at once noted, and also the much larger viewing apertures just above the desk, in place of the smaller port-holes of last year's design. An optical × 3 magnifier is provided at the front window.

A considerable simplification is the abolition of the air-locks, rendered possible by the improvement of the pumping system, a part of which, viz., the oil diffusion pump, can be seen below the desk in

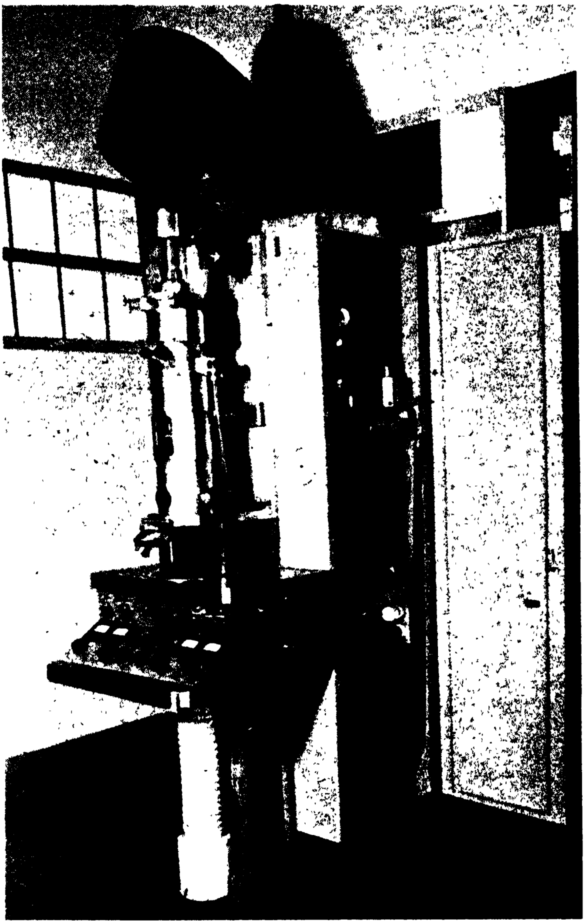

FIG. 174.—E.M.U. electron microscope by R.C.A., with all casings and doors opened.

Fig. 174. As it is now possible to exhaust the whole tube to $10^{-4}$ mm. of mercury in a minute and a half, there is actually a saving of time as well as trouble in spite of the omission. The number of thermionic valves, some of which can be seen in the cabinet, has also been reduced from 52 to 25.

The most notable additions are the diffraction camera attachment and the stereoscopic device. Of these, the former is located within the tube just above the windows, and enables a narrow beam of rays from the upper lenses to be so focussed and directed that diffraction figures can be taken either by transmission or reflection.

Stereoscopic records are taken by means of the slightly inclined, knurled knob about a third of the way down the main tube in Fig. 174, which operates a device for tilting the specimen. Two micrographs are taken in succession, first with the holder tilted 4 degrees to the left, and secondly with an equal tilt to the right, and the resulting pair of prints are mounted side-by-side as with other stereoscopic photographs. By enabling the eyes to see partly round the object, the effect of solidity is conveyed.

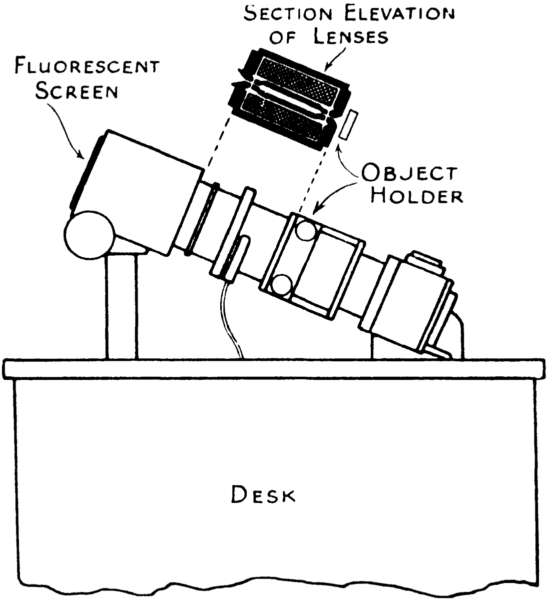

FIG. 175.—R.C.A. desk pattern microscope, showing section view of lenses (inset).

The H.V. section has now been designed to require air-insulation only, and the oil tank is therefore omitted ; while ventilation is by ordinary convection, there being no fan. There is a centre-seconds clock for timing exposures, and an " antinous " cable release for the shutter. The power demand is 1.5 kW at 110 V.

R.C.A. DESK PATTERN. Much of the complication in the construction and use of the type just described is derived from the adjustments involved in altering the magnification and re-aligning the beam. A much smaller and simpler form of electron microscope has therefore been developed by the R.C.A. Co. following the success of the larger model, for use in many situations where the magnification need not be either variable or extremely high. Many industrial and research purposes are adequately served by a fixed magnification of 5,000, with the possibility of increase by photographic enlargement of as much as 20 times to 100,000 diameters without exhausting the detail in the original negative. This performance is given by the instrument shown in Fig. 175.

Here the length of the tube is only 16 in., and the anode voltage is 30 kV. Since so small a tube can be evacuated in about two minutes, air-locks are unnecessary. The hot cathode is surrounded by a cathode shield, forming an electrostatic condenser lens as shown previously in Fig. 15A, and the other two lenses are neatly provided by the one electromagnetic circuit indicated by the sectional inset above the elevation in Fig. 175. It will be seen that the fluxes for both lenses are in series, enabling the one coil to serve for the two. Since the magnification is not variable, the whole lens assembly can be made rigid, and aligned once and for all before the instrument leaves the works.

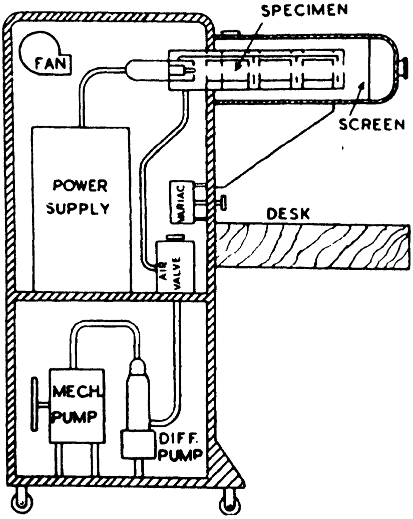

Fig. 176.—Electrostatic microscope by the G.E. of America, sectional elevation.

The fluorescent screen is formed on thick glass, fixed at the upper end of the tube where inspection is most convenient. Photography is effected by rotating a photographic plate up against the inside of the screen by means of the turn-button seen just below it. Both the mechanical air-pump and the electrical gear are inside the desk, but in the latest model the oil diffusion pump is designed with a sloping tube to fit just below the main tube.

**G.E. Electrostatic Microscope.** An interesting microscope employing electrostatic lenses has been recently constructed by the G.E. Co. of America. The diaphragm type of lens has been adopted, and increased magnification has been secured by employing more than the conventional number of stages for the lens system. This is illustrated in Fig. 176, in which the microscope tube consists of the horizontal member projecting to the right from the top of the enclosure. The discharge tube is at its left-hand end, the figure showing the hairpin-shaped hot cathode just inside the main tube, which is only 11 in. long from the cathode to the fluorescent screen, seen as a vertical line near the right-hand end of the tube. This screen is viewed by means of a glass lens, and records are also taken by photographing the screen image, so that the last stage of magnification is effected by ordinary light optics.

Most of the magnification is however obtained by means of a series of three electrostatic lenses, each consisting of three consecutive diaphragms of the general type illustrated in Fig. 15B. Of these, the two outer diaphragms are at earth potential, while the inside members are insulated and are all connected to the same high voltage. The latter is obtained by means of a conventional type of power unit working at voltages up to 35 kV and contained in the tank shown on the shelf. Smooth variation of this voltage is secured by the " Variac " control unit from a low value up to the maximum. The vacuum pumps are contained in the lowest compartment and consist of a relatively small single-stage oil diffusion pump backed by a rotary mechanical pump.

The great advantage of electrostatic lenses is that the power supply can be obtained direct from the mains through the medium of the usual transformer and rectifier equipment, without elaborate smoothing arrangements. This is possible because voltage variation produces equal and opposite effects upon the lenses and the wave-length, as regards the focal length of the whole combination. A great simplification is obtained by this means, and it becomes possible to get exposures of any length with the certainty that the image will remain of constant size for the whole period.

A magnification of × 500 is obtained electronically, which can be increased by optical or photographic enlargement to 7,000 or 8,000. A light, portable and comparatively inexpensive instrument is thus produced, which can be of great use for many industrial and scientific purposes.

**Mounting of Specimens.** The great majority of objects for the microscope must be mounted upon a transparent support. For visible light, glass forms the most suitable material, but in common with all substances, whether solids, liquids or gases, is opaque to the electron beam if the thickness much exceeds $10^{-6}$ cm. ($0{\cdot}01\ \mu$). A new technique has therefore been built up, notably by Dr. L. Marton, whereby the conditions are met.

Specimens for the R.C.A. microscope are usually mounted at the lower end of a small cartridge-shaped tube, somewhat under an inch in length, with a bore of about 0·02 in. diameter, as shown in Fig. 164. A membrane of about the required thickness ($0{\cdot}01\ \mu$) is first formed by allowing a small drop of collodion or celluloid " cement " to fall on to the surface of water and spread out. This quickly sets, and is then brought into contact with its immediate support, a small circular disc of 200-mesh wire gauze, less than ⅛ in. in diameter, by carefully placing the latter upon the solidified cellulose. Gentle pressure upon the gauze causes it to adhere to the film.

By means of delicate handling tools, the coated discs are separated from the rest of the membrane, lifted from the water, inverted so as to bring the film side uppermost, and placed upon a miniature pedestal. Here the water clinging to the surface is removed, and a drop of a liquid containing the specimen in suspension or solution is placed upon it and the liquid allowed to evaporate. The whole is then placed and held in position by a small cap on the cartridge, which in its turn is inserted through the air-lock into the interior of the microscope tube, *i.e.*, into the space about to be evacuated.

**Performance of Electron Microscope.** Although so short a time has elapsed since the electron microscope became a practical instrument, it has many achievements to its credit, and what is more important, it has given sure promise of much greater successes to come. Some of these have already been indicated ; but a large space would be required in order to suggest even the main portions of the field waiting to be covered. Most scientific investigators will, however, already have experienced instances where further progress is barred by the inability to see what is going on. These obstacles are now being effectively removed, or at least greatly mitigated. A few notes with regard to typical cases will be of interest.

DUSTS. Solid particles which are so small that they are capable of being suspended in the atmosphere for considerable periods have been the subjects of numerous investigations. Their effect on the membranes of the human body is one reason for their importance, while another is the danger of disastrous explosions due to the more inflammable materials, such as coal-dust, starch and flour. Much work has been done in connection with apparatus for separating out and counting dust particles in connection with ventilation problems.* Yet the best optical microscope is incapable of rendering visible the finer particles floating in the atmosphere, an appreciable proportion of which are smaller than 0·2 μ. The majority of the particles found in the human lungs are less than 5 μ in diameter, and much work remains to be done in this connection.

Objects of this description are among the most suitable for electron microscopy. An example may be found in the asbestos fibres of only 0·02 μ in thickness which have been recorded by Continental investigators.

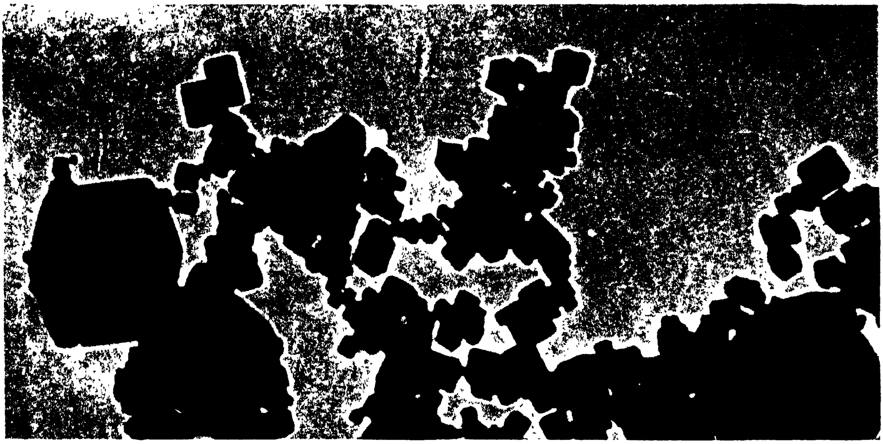

FIG. 177.—Magnesium oxide. × 70,000.

SMOKES. Smokes are in reality clouds of particles formed by combustion, and hence closely resemble dust; while they possess an even higher proportion of constituents that are beyond the range of the optical microscope. Many researches have been carried out upon them in connection with problems in the efficient use of fuel, the formation of fog, and hygiene, to name only three instances. One example has already been given in Fig. 143 from an investigation by G. D. Preston at the National Physical Laboratory using magnifications up to × 23,000 † in connection with fumes of zinc oxide, revealing that they contain needle-shaped particles about 0·4 μ long and less than 0·04 μ thick. The magnesium oxide crystals in Fig. 177 (× 70,000) form a contrast, having apparently a hexagonal, but actually a cubical shape.

COLLOIDS. Colloids consist of particles small enough to execute

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* See Goodall, "Physics and Protection against Industrial Dust," *J. Sci. Insts.*, Vol. 19, March, 1942, p. 33.

† See *Nature*, March 8th, 1941, p. 298.

Brownian movements, immersed in a liquid magma. A great deal of research work has been done upon them during recent years, in spite of the impossibility of seeing the particles concerned. A method of detection has been much employed (the so-called ultra-microscope) in which the material is illuminated by a transverse cone of light, which can be reflected by particles as small as 0·005 $\mu$ and the reflections perceived by means of a powerful optical microscope. This method is obviously a poor substitute for magnified vision.

One of the most important colloids is gelatine, which forms the basis of the photographic film. Great improvements have been effected within the past fifteen years through increased knowledge of the properties of the film, and the behaviour of the silver and its compounds present in extremely fine subdivision in the mass. A fresh impetus has been given to the work by the electron microscope, through its enabling the changes to be actually seen. One surprising discovery, which has just been made by C. E. Hall of the Eastman Kodak Co., is that the silver image does not consist, as was previously supposed, of a spongy mass of silver formed in the silver halide grain, but of a thin tangled ribbon about $2 \times 10^{-6}$ cm. wide, dispersed in grains each averaging less than $10^{-4}$ cm. in any direction.*

MOLECULAR THEORY. One of the most amazing achievements of past scientific research has been the working out of the composition of matter without any possibility of seeing the structures which were deduced. It is probably true to say that none of the men who were responsible for the atomic and molecular theories can have hoped that these almost inconceivably small bodies could ever be seen ; but the position is very different to-day.

Assuming the lower limit of perception for the optical microscope to be a particle with a diameter of 0·2 $\mu$, and the present power of the electron instrument to be 100 times that of the former, it should be possible to see a particle 0·002 $\mu$ in diameter. Now the size of the ether molecule has been calculated by Perrin to be about 0·0006 $\mu$ ; and since a magnification $10^3$ times as great is theoretically possible when the electron lens has been perfected, it is difficult to place a limit to what the future has in store. Already bodies only about three times the diameter of the average molecule can be seen, according to the above calculation ; while large chemical molecules have already been recorded in such detail as to exhibit their structure. As an example of what is already being accomplished in chemical micrography, a sample of partly polymerised vinyl chloride, a rubber-like material magnified 54,000 times, is shown in Fig. 178. This micrograph is typical of the structures observed in both natural and artificial rubbers, a number of

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* See *American Photography*, Feb., 1941, p. 141.

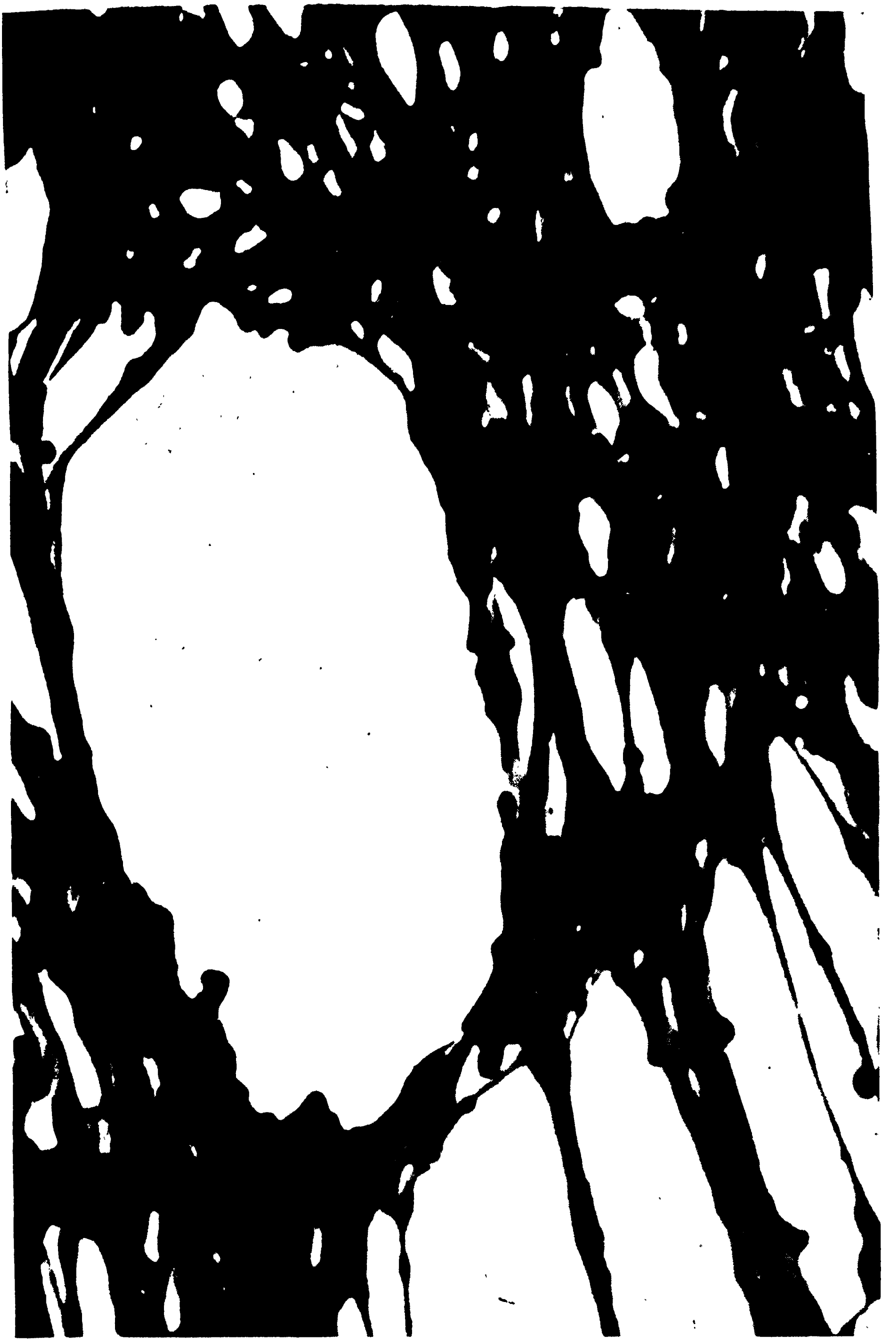

FIG. 178.—Vinyl chloride partially polymerised (vinylite). × 54,000.

which have been investigated with the electron microscope by Hall * and others at the Massachusetts Institute of Technology with very interesting results. Two distinct fibre structures are assumed by the materials, which are capable of changing from one to the other as the result of suitable treatment. The form shown in the figure is a network of beaded fibres, which is broken down by mastication to a much simpler arrangement of strands, containing frequent nodules of relatively larger diameter, such as 0·2 $\mu$. These two varieties represent the " gel " and " sol " forms respectively ; and it is noteworthy that vulcanisation by means of sulphur is able to reverse the change, by reproducing the closely-branched network characteristic of the " gel " type. The way in which colloidal carbon filler joins up with the network has also been determined. This and the following micrographs were taken with the R.C.A. instrument shown in Fig. 172.

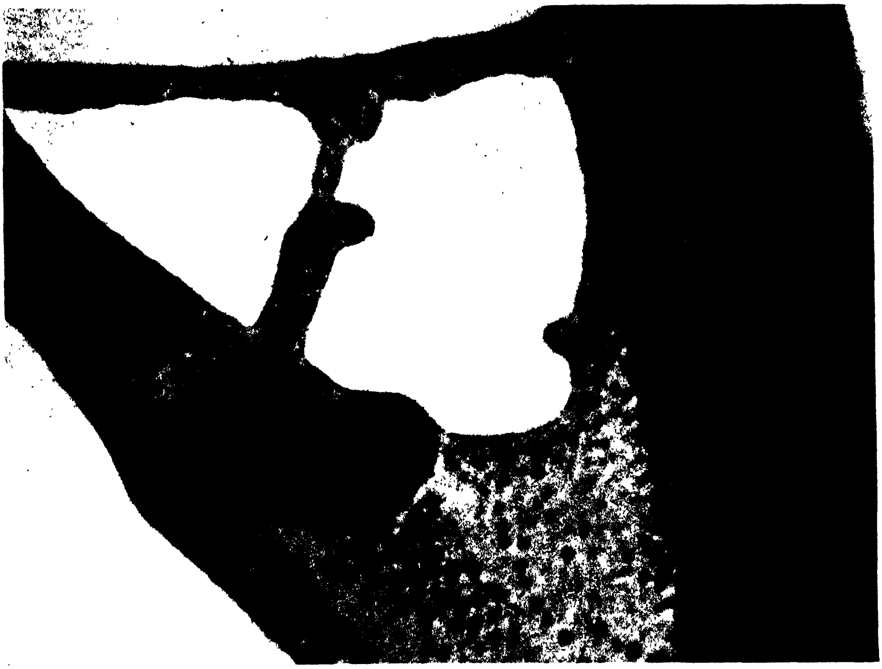

FIG. 179.—Polymerised vinyl chloride. × 200,000.

Fully polymerised vinyl chloride (P.V.C.) has even larger molecules than vinylite, and it is significant that the micrograph of this material, shown in Fig. 179 to a magnification of × 200,000, presents an evenly

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* See *Natural and Synthetic Rubber Fibres*, Ind. Eng. Chem., Vol. 36, 1944, p. 634.

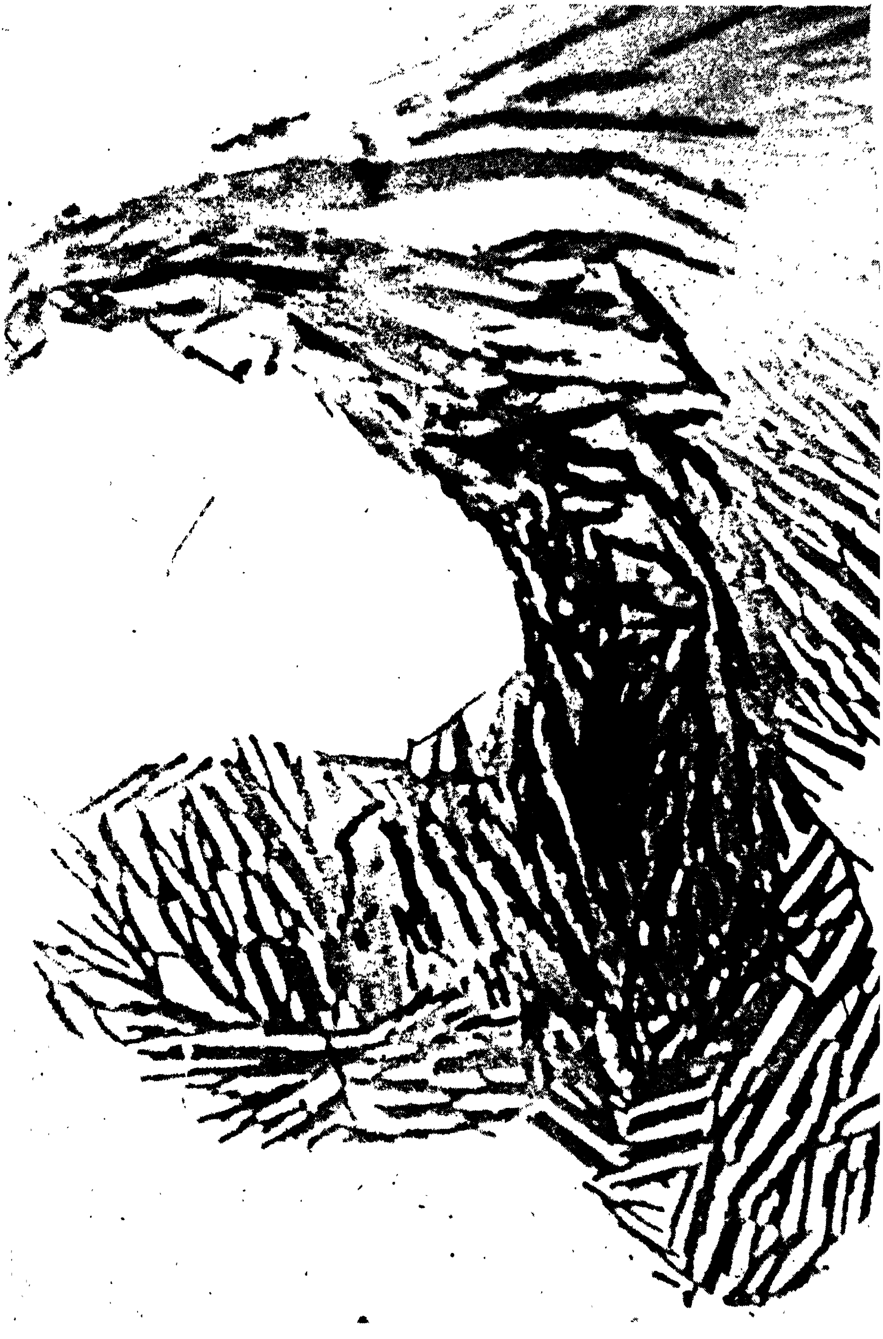

FIG. 180.—Tobacco mosaic virus. × 55,000.

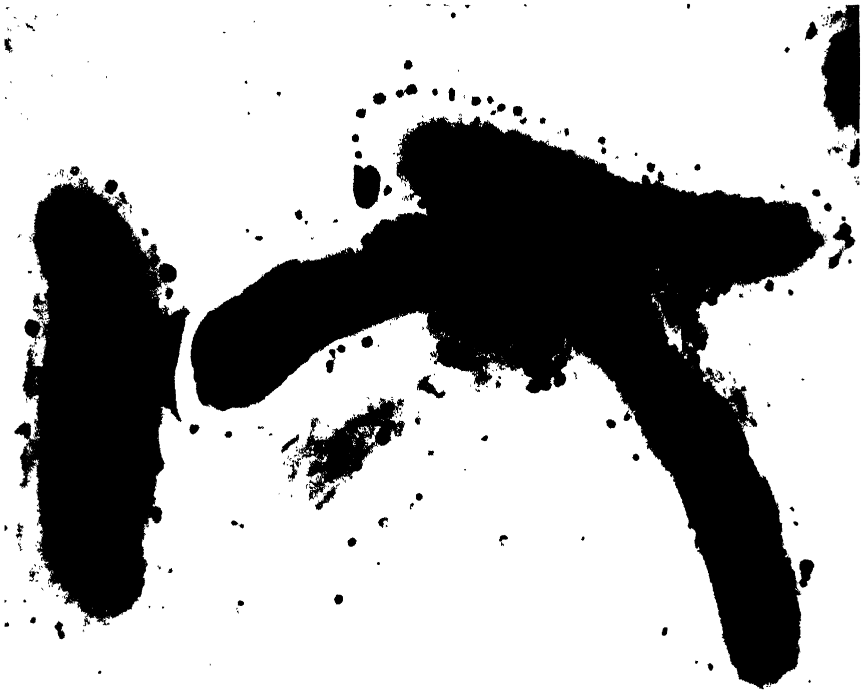

FIG. 181.—Tuberculosis bacilli. × 24,000.

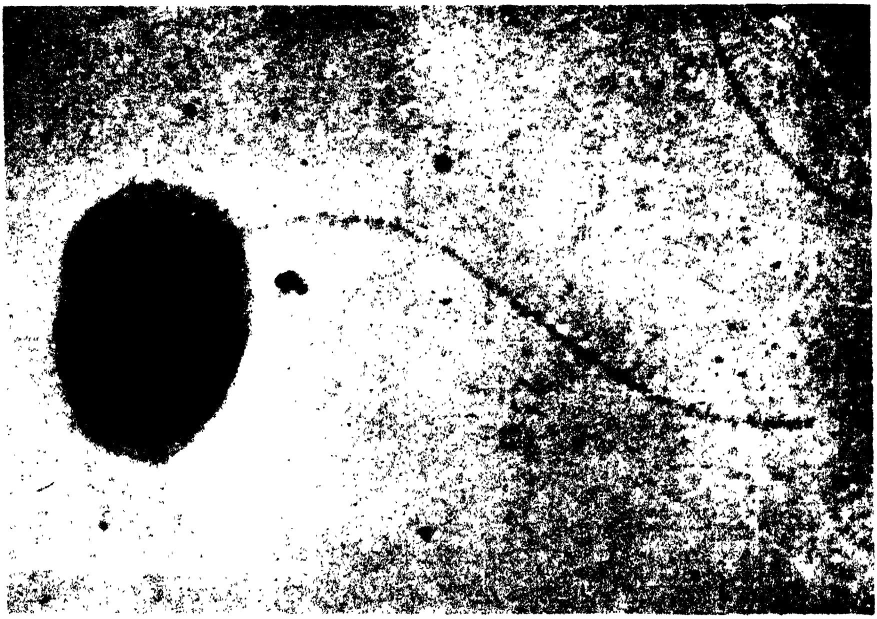

FIG. 182.—Typhoid microbe. × 41,000

mottled appearance, the spots being of just the size which calculation shows the molecules would attain.

Research in the field of natural and artificial rubbers by the Goodyear Co. of America will exemplify the value of the new instrument to the chemical industry. It was known that the synthetic product differs from natural rubber in four well-marked respects : it cannot be concentrated by centrifugal methods, its viscosity is greater for a given solid content, it is able to impregnate fabrics more readily, and it is more stable mechanically. These peculiarities were all explained by a comparison between the electron micrographs of the two materials, which showed that the particles in the synthetic latex are not only finer but are more uniform than in the case of the natural latex ; the

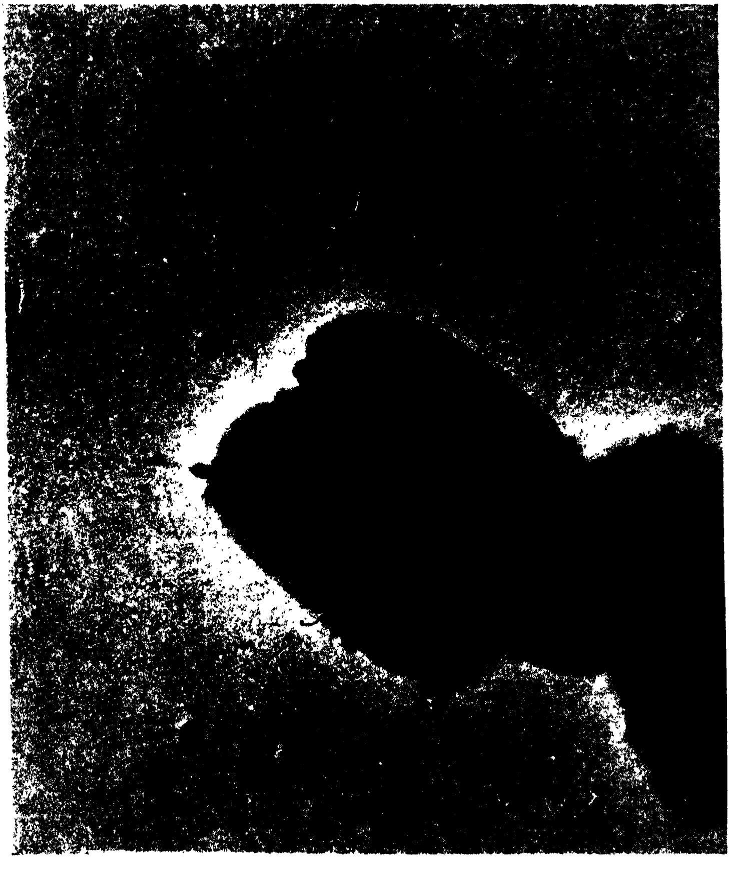

FIG. 183.—Part of *Escherichia coli* bacillus, attacked by bacteriophages. × 33,000.

ranges of particle diameters in millionths of an inch being 0·8 to 7·2 and 4 to 160 respectively.*

BACTERIOLOGY AND MEDICINE. Reference has already been made to the long-standing mysteries that will in all probability be solved in connection with the origin and treatment of disease. Well-known instances of such gaps in present-day knowledge are the causation of the common cold and of rheumatism. The former, for example, is thought to be due to a virus so minute as to be beyond the range of microscopes of the past. A virus (the tobacco mosaic) which has figured in recent bacteriological research is now shown by means of a magnification of 55,000 in Fig. 180. A portion of a tuberculosis bacillus, with details of its body structure, is shown in Fig. 181 (× 24,000); while a typhoid microbe (× 41,000) is exhibited in Fig. 182, in which a long flagellum is seen coming from the right upper part of the body.

It is quite a reasonable expectation that medical men will be able to watch the action of drugs and other curative agents upon disease germs, as well as to identify all the causes of ill-health. The exact knowledge so gained cannot but be of the greatest benefit to the human race. An example of what has already been accomplished in this direction is shown in Fig. 183, where a bacillus inhabiting the human intestines is seen being attacked by a swarm of anti-bodies.

APPLIED CHEMISTRY. Many chemical processes employed in industry stand to benefit as a result of detailed visual inspection. The mechanism whereby catalysts perform their gratuitous functions will probably be revealed. The constituents of a fertile soil will be rendered visible and how they do their work; while the effects of fertilisers will be scrutinised. What is required of insecticides and fungicides will be ascertained from direct observation. The compounding and setting of a synthetic resin will be able to be carried out more perfectly with a more intimate knowledge of the setting reactions.

Fibrous industries, such as paper-making, textiles and leather-finishing, will benefit from the more precise data as to the effect of various old and new chemical materials on the strands. Cement and ceramic industries, which have to deal with very fine grain sizes, will also welcome the higher magnification: while the same holds good for paint and enamel compounding. The manufacture of arc-light carbons may also fall into this category, since grain size is considered to be one of the main factors involved in smooth burning.

METALLOGRAPHY. A great amount of information upon the structure of metals and alloys has been obtained within recent years by magnifying the etched surface. When visible light is employed, this is usually done by means of reflection, a method that is not applicable to cathode rays ; but already an alternative had been devised, in the use of transparent casts of the surface in question, which were dyed and then viewed by transmitted light. The replica method, used with the electron microscope, is capable of giving high magnifications and very definite demarcations. There are two principal variants, which may be called the single and double transfer methods respectively.

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* See *The Engineer*, November 12th, 1943, p. 396.

To begin with, the surface of the specimen is carefully polished, usually with magnesia powder (MgO), and is etched in a specified solution for a measured time. For example, it is found that 10 to 15 seconds in a saturated solution of picric acid in alcohol gives about the right depth for a plastic replica of 1·1 per cent. carbon steel.* The single transfer process consists of coating the surface so prepared with some kind of dissolved material, such as collodion, or nitro-cellulose, which can be detached from the specimen. At first the separation was accomplished by dissolving away the metal by means of a suitable acid. This had the disadvantage of destroying the specimen, and a method was therefore worked out by Schaefer and Harker in which a material is used which is strong enough to be peeled off without deformation. The specimen is dipped in a solution of polyvinyl chloral in ethylene dichloride, and allowed to set in air with its face vertical. A coating having a thickness increasing gradually from the upper to the lower edge is the result, with a considerably thicker portion near the lower margin. The specimen is then immersed in water, and the thicker rim is gripped by a pair of tweezers and eased away from the metal. By pulling the film back on itself, most or all of it is easily detached. It is finally treated like the support of ordinary specimens by being left floating with its " smooth " side uppermost, and the gauze disc lowered upon it.

The double transfer, or negative-positive method, was devised by the R.C.A. Co., and consists of forming a metal cast by evaporating metallic silver upon the surface in a vacuum chamber.† This film is reinforced, if necessary, by electroplating, until it has sufficient strength to be removed from the surface by mechanical force. A positive film is then formed by flowing thin collodion over the metal cast ; and when it is set hard, the silver is removed by means of nitric acid. The example in Fig. 184 is of pearlitic steel, the magnification being × 25,000.

**Characteristics of Electron Micrographs.** The chief advantage which the electron micrograph possesses is, of course, its greatly increased scale, about which sufficient has been said. Another characteristic, which is usually an advantage, is the great depth of focus. This is an inherent property, and may be observed notably in Fig. 178, where every part of the object is in sharp focus, whereas a light microscope would render sharp only those parts at a given level, all others being out of focus. There are occasions, however, when the latter feature is required, in order to be able to isolate one element from the others, and by selective focussing to obtain a measure of the distance between successive strata or layers in the " up-and-down " direction ; and in these cases the visible or ultra-violet light microscope is at an advantage.

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* See Schaefer and Harker, *Journal of Applied Physics*, July, 1942, p. 427.

† See Zworykin and Ramberg, *Journal of Applied Physics*, September, 1941, p. 692.

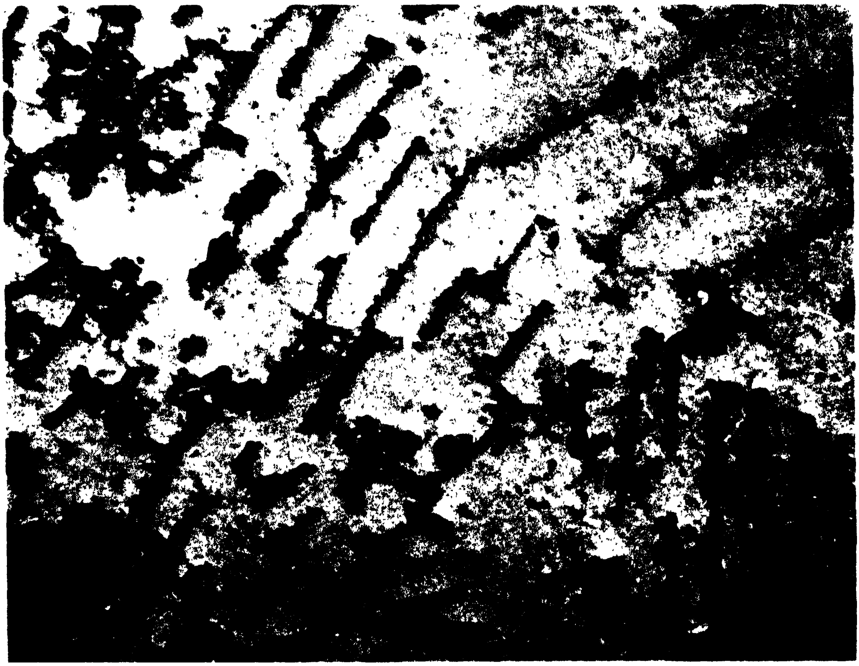

FIG. 184 —Pearlitic steel. × 25,000.

It must be remembered that high power brings its own difficulties with it. " Finding " a given part of the object is of increased difficulty ; and was assisted in the M.V. instrument by the built-in light microscope which carried out the preliminary search. The method described on pp. 189 and 194, of locating the " first " image before proceeding to the second has, however, proved the more convenient, and much the simpler, solution to the problem.

Further, the bombardment of the object with high-speed electrons produces heat which is capable of damaging delicate substances. Certain types of specimens cannot therefore be viewed in this way, while others require care as regards intensity of beam or length of exposure, and possibly special preparation. An additional restriction is that the object is situated in a high vacuum, and must therefore be dry. Great difficulty is experienced in viewing anything but " dead " specimens, and, in consequence, movement such as that which would have been so entertaining in Fig. 183 must almost inevitably be " frozen," and require a number of successive and similar operations to show progressive action.

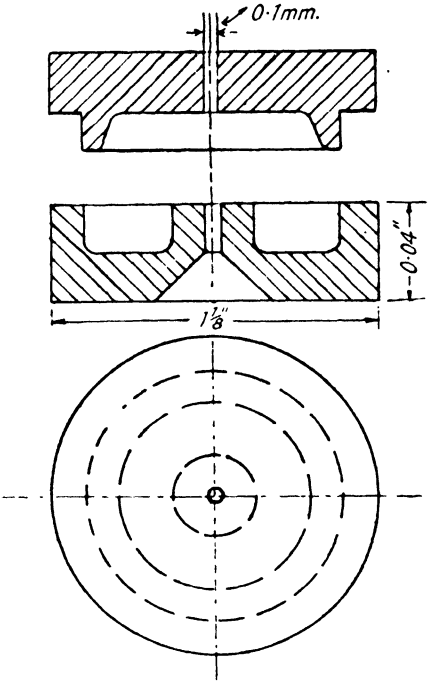

FIG. 184A.—Live specimen capsule.

Within the past twelve months Abrams and McBain of Stanford University have devised a successful method of viewing specimens without desiccation being entailed. They employ a small enclosed chamber of platinum shaped rather like a diminutive pill-box, as shown in the enlarged section and plan forming Fig. 184A, the outside diameter being only ⅛ in., and the central hole 0.1 mm. The bottom of the annular recess is covered with adhesive wax such as Cenco " Tackiwax," into which the projecting cylindrical rim from the cover is pressed ; while the two small holes are closed on the inside by cellulose films only

·05 $\mu$ thick. These are formed by floating a drop of a 2 per cent. solution of collodion in amyl acetate upon a cleaned mercury surface, and raising the bored disc through the mercury into contact with the solidified film. The object is then placed on the lower cellulose disc, and excess liquid may run down into the annular space. Both wax seal and cellulose windows readily withstand the negative pressure of one atmosphere.

Another limitation is the impossibility of using the surface of a thick material as an object, as can be done with the optical microscope by means of reflected light—*e.g.*, metallography. However, the difficulty has been largely overcome by the transparent replica method described on p. 207.

**General.** Only those cases have been mentioned in the above which directly involve the treatment of ultra-microscopic particles or strands. The whole practice of microscopy will, however, be beneficially affected through the ability to progress far beyond present limits. In mineralogy and metallurgy, for example, new knowledge is to be expected on this account. It would indeed be difficult to name a scientific or industrial sphere in which the electron microscope is not likely to find an application in the near future.

## CHAPTER TWELVE

# CONSTRUCTION, OPERATION AND MAINTENANCE

ALIKE in principle and construction, the cathode ray tube is not very different from a large thermionic valve ; and the complete oscillograph set in its turn closely resembles the wireless receiving set in both design and operation. Since the latter apparatus is already familiar to readers, there is need for only a few additional details as regards the treatment of the cathode ray oscillograph.

A distinction must, however, be drawn between the glass and the metal tube types, in that the former must be obtained ready-made by all but a very few specially favoured workers ; and construction will take the form of the assembly of the tube along with the necessary valves and accessory circuits into their containing case. Although much more expensive to purchase than the foregoing, the metal tube type is not beyond the constructional powers of an accurate fitter and turner.

The general use and upkeep of the two types are also different ; and they will accordingly be considered separately throughout the chapter.

**Construction.** (*a*) GLASS TUBE OSCILLOGRAPHS. A considerable amount of information has already been given in the first four chapters concerning the principles and design of the glass-tube set. After the forms of the various components and the conditions governing their selection had been described in Chapters I and II, the power units, time bases, synchronising schemes, modification of independent bases, attenuators, amplifiers, time markers and cases were dealt with in Chapter III. The principal arrangements of set in use to-day were described in Chapter IV, with discussions on the advantages of the different methods of focussing, the requirements as regards anode voltage for various conditions, and the nature and arrangement of the controls. Other design details are given during the descriptions of the typical sets.

Readers will find a quantity of practical information in these chapters with regard to the construction of an oscillograph set. Since the actual constructional methods are closely similar to those employed for wireless receivers, there is no need to dwell upon such details as fixing, arrangement and wiring. For those who would like to begin their acquaintanceship with the subject by building a small and inexpensive but very useful set, the paper by Macfadyen and Day to which * reference is made in Chapter IV (pp. 60–1 and Fig. 38) is strongly recommended. Not only is the apparatus described in detail, including the location and methods of supporting all the components, but also the sizes of condensers and the design of the transformer, case, and other parts.*

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* See " A Portable Cathode-ray Oscillograph," *J.S.I.*, Vol. 17, October, 1940, p. 49.

There is, however, one requirement that does not exist in the radio receiver, namely the support of the long cathode ray tube. In order to guard against the effects of rough treatment, rigid holders and fixing should not be used, except possibly in the case of relatively small tubes and tubes mounted vertically. Most are used horizontally, and then require flexible supports at the screen end and at the neck near the base. Metal-to-glass clamps are to be avoided. A common method employs a holder fitted with helical springs that press the screen end against a rubber ring, fixed to the inner-side of the plate pierced with the large hole through which the screen is viewed. This is the method described by Macfadyen and Day. It is important that the screen should register at a fixed position to ensure accurate focussing when a pre-set camera is slid into place for recording purposes.

It should be remembered that heat is emitted from several parts of the equipment, and there should be sufficient provision for ventilation to ensure a safe temperature. This should especially hold good with regard to the base of the oscillograph tube.

As regards the scheme of connections, care should be taken that the insulation between the cathode and its heater is not overstressed. The best practice is to connect the cathode to the mid-point of the heater, but in any case the voltage between the two must not exceed 50. It must also be remembered that the electron beam constitutes a direct current emanating from the cathode, for which a return path is necessary. There must therefore be a connection capable of passing a D.C. between the cathode and each other electrode.

(*b*) METAL TUBE OSCILLOGRAPH. The continuously evacuated tube requires the services of a good metal-worker. Its general form has been indicated quite closely in the introductory article, and the principles underlying the proportioning of the various parts can be understood by regarding it as the metal equivalent of the glass tube. Several of the components require insulating supports, such as the cathode (in the discharge tube), and the deflector plates, and porcelain bushes are usually employed for the purpose. Constructional notes with regard to the various parts are given below ; but it should be understood that existing practice is not necessarily the only possibility. For example, more use might be made of sheet metal and soldered joints.

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* Reference may also be made to a recent article in *Radio News* by R. P. Turner, " '5' Oscilloscope Design : employing government surplus tubes," Aug. 1945, p. 37.

TUBE. The tube is generally made in sections of convenient length, united by flanges that are substantial enough to maintain the vacuum without requiring undue trouble in fitting. There are three alternatives as regards packing or lagging.

1. Grease. The faces of the flanges are made as true as possible by turning, and are then finished by lapping with fairly coarse grinding paste upon a surface plate. It is important not to overdo the finish, as a matt and not a shiny surface is required. Lapping should not take more than 5 or 10 minutes at the outside. Care should be taken to renew the paste every few minutes, two or three changes being needed during the above time. Finally, the surfaces should be carefully cleaned, covered with a thin layer of the selected lubricant, and then slid together. The grease should be thick enough to resist being squeezed out by the pressure between the flanges.

If the instrument is not to be moved nor subjected to vibration, no further fixing of the flanges is necessary, as the air-pressure will hold them firmly together. External clamps, to the number of four or more, may, however, be added, and are needed if the oscillograph is required to be moved. Risk of leakage at the joints is the principal factor militating against portability of the metal-tube oscillograph.

The grease may be one of the compounds specially made for the purpose, such as " Apiezon " No. M ; or a rubber mixture may be used. Chalmers and Quarrell * recommend a rubber paste made by dissolving 2 to 5 per cent. of crepe rubber in petroleum jelly at 100° C., and removing dissolved gases by heating *in vacuo* at the same temperature. The higher proportions of rubber are only needed for the higher ambient temperatures. Castor oil may also be used as a solvent.

2. Rubber. A natural or synthetic rubber washer may be employed, and gives a more convenient joint than grease for frequent making and unmaking. It is useful, for example, for the camera box. The surfaces are lightly lubricated with glycerine or a similar liquid. In the case of natural rubber which is vulcanised with sulphur, the constant vacuum seems to have the effect of removing the sulphur and thus causing deterioration ; and neoprene synthetic rubber, which does not contain sulphur, is frequently preferred.

3. Solder. The joints may be soft soldered, or even brazed together. This practice naturally gives the most robust and permanent result, which will readily withstand transport and vibration. A common practice is to employ ordinary solder, melting at about 200° C., for " permanent," and Woods metal, melting at about 70° C., for " semi-permanent " joints.

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* See " The Physical Examination of Metals," Vol. 2, *Electrical Methods* (Arnold), p. 202.

For flanges in general, there is no need for the joint faces to be flat; and there is scope for originality in the production of simple intermeshing or labyrinth designs.

As regards material, the tube is generally made of drawn brass tubing, which can be relied upon to be free from pores. For the same reason, the flanges, which may be soldered on to the tubing, are of some such material as Admiralty gun-metal.

DISCHARGE TUBE. There is considerable latitude as regards the design of the cathode and its tube. A metal tube ending in a porcelain bush for the cathode is one alternative, or an all-glass design may be employed. Professor Finch used a champagne bottle with the bottom removed for his original model, and this was so successful that his tubes, exemplified in Figs. 4 and 165–6, have retained their initial shape.

It is important to bear in mind the production of X-rays where the electrons strike the end of the discharge tube, and to counter their injurious effects. They can do harm in two ways; first, they are a direct menace to the operator through their ability to cause malignant dermatitis, and secondly, they may pass down the tube and cause serious fogging upon the photographic film. Lead shields are fitted to obviate both effects; the first by an external cylinder round the lower part of the discharge tube, and the second by a disc inside the latter and resting on the anode block.

A certain proportion of other ("retrograde") rays are also produced, which are not deflected with the electrons in the beam, and again cause fogging. They are diverted in many designs by inclining the discharge tube, so that when the record is not being made, all the rays pass into the trap. Untrapping is effected by positively deflecting the cathode stream through the aperture, the retrograde rays still remaining trapped.

DEFLECTORS. There should be no difficulty in designing a bushed stem for the entry of each deflector. The simplest arrangement does not provide for external adjustment of the deflector position, the tube having to be taken apart for this purpose. If adjustment from the outside is desired, it may be arranged either by means of a sliding stem, rendered vacuum-tight with grease, or by the use of a short length of the thin metal "bellows" tube manufactured for the purpose.

FOCUSSING COIL. A suitable winding for the concentrating coil would be about 12,000 turns of No. 33 S.W.G., double-silk-covered wire. Arrangements should be made for tilting it in order to direct the beam in a truly axial direction; three micrometer screws constituting the usual method. The winding given has a resistance of about 1,760 ohms, and is appropriate for 230 volts, in series with a variable rheostat for adjusting the current between the limits of 0·05 and 0·1 amp. The above does not require the coil to be " ironclad."

FLUORESCENT SCREEN. The fluorescent material could consist of luminous paint, which normally contains zinc sulphide ; or preferably of one of the numerous fluorescent powders made up for the purpose. It may be applied to a card held in a pivoted metal carrier and moved by an external turn-button on the end of a spindle passing through a close-fitting greased bush. The powder is applied to its support, whether glass or card, by first covering with an adhesive such as an alkaline silicate, and then blowing the fluorescent material on to the sticky surface. A minimum amount of adhesive should be used, and the powder that does not adhere should be shaken off.

CAMERA. The exposure may be effected by using either the hinged fluorescent screen, or the trap-plates, as a " shutter." There is scope for individual ingenuity as regards the design of the film or plate holder. Roll films are recommended, with the changing arrangement copied from that in the familiar roll-film camera or " adaptor." The spool is wound by an external turn-button and spindle passing through a greased bush.

**Operation.** GLASS TUBE. As with construction, the operation of a glass-tube oscillograph is very similar to that of a wireless receiver and much simpler than in the case of the electromagnetic instrument. In robustness it is comparable with a portable wireless set, so that transport can be carried out with all components in place, and the set ready to go into action as it stands. When first sent out from the works, however, the main tube is frequently packed separately, and insertion into its holder is the only change needed to put the whole into commission.

There is much less risk of sudden damage being inflicted than with an indicating meter, and the various precautions have long life as their chief object. They can be summed up in two words by the popular phrase, " Go easy " ; or, in other words, do not employ a higher anode voltage or a brighter spot, or keep the tube in operation for a longer time, than is necessary. There are two perishable components in the tube itself, viz., the cathode and the screen ; while the condensers are probably the most delicate external components. All these are preserved by the above rule.

The screen is the principal innovation as compared with the wireless receiver, and its welfare therefore merits a few words. First, there is no need to adjust the spot at its maximum brightness for every test. For visual observation, a relatively dim trace is sufficient, especially if care be taken to restrict the amount of room lighting in its vicinity ; or if a screen-hood be employed, such as that on the model shown in Fig. 41. Requirements may be more stringent when a photographic record has to be taken, and if a specially intense spot is used for this purpose, it should be " turned up " immediately before the exposure and back again immediately after.

Excessive brilliance is the more liable to cause deterioration the slower the movement of the spot, and it is particularly necessary to arrange the procedure so as to obviate the beam remaining stationary unless in a dim condition. Neglect of these precautions will probably cause an insensitive patch or line in the screen.

The chief precaution in order to guard against mechanical breakage of the tube is to avoid scratching or scoring the surface of the glass. Even a scratch that is so slight as to be nearly invisible may form the starting point of a complete fracture.

Connecting up is a simple matter, as all terminals are clearly marked on any modern set. The " earth " and mains leads naturally come first ; but before the voltage is switched on, the operator should check the position of the mains-voltage link (or switch) upon the set, to confirm that it is engaging the contact marked with the actual supply voltage. The earth lead should go to a water-pipe or other good earth connection, unless the test circuit requires that earthing be effected elsewhere. As examples, the connection diagrams in Figs. 139 and 140 should be compared. When accuracy of reading is important, the best point in the circuit for the earth connection is the final anode. Earthing the cathode will render the beam liable to be deviated by an earthed body near the screen, especially when the anode voltage is low.

The " work," *i.e.*, the phenomenon under investigation, is connected to the deflectors, requiring two leads if the internal time-base is to be used, or if only a single pair of deflectors are to be energised ; and two pairs if the two deflections are produced by voltages outside the set. In all cases the two leads of a pair should be twisted together ; and this should be done even when two of the plates are connected together inside the tube, involving a common return to which one lead of each pair is connected.

After the supply voltage is switched on, there should be a wait of about 30 to 60 seconds to permit the set to " warm up," *i.e.*, to enable the various heaters to produce the correct working temperature. The spot should have been switched off when the set was last used by turning the " Intensity " control knob right round to the minimum stop, and the positioning, focussing, and horizontal gain controls should all be turned to their half-way points.

The time base, or " horizontal sweep," should first be put into action, to ensure that the spot is in motion as soon as it is brought into being ; and for this the vertical amplifier should be turned off, the frequency control set at about 50 c/s, the synchronising switch put at

" Internal " (or the synchronising terminal connected to the Y deflectors), and the sweep switch closed. When all this has been done, the Intensity control can be slowly turned until the spot begins to appear in the form of a horizontal line. The focus and intensity knobs can then be adjusted at the same time until the trace is sharp and sufficiently brilliant. Adjustment of the horizontal and vertical position controls will bring it to the middle of the screen, and the length can be modified by means of the horizontal gain control.

Everything is now ready for receiving a signal ; and the most convenient one to start with is the (A.C.) supply voltage. A pair of leads are taken from the mains, or from a L.V. winding on the power unit, to the vertical input terminals, and the vertical amplifier is turned on. Operation of the vertical gain control will cause the horizontal line to develop into the voltage wave of the power supply. The effect of the sweep frequency control should be experimented with. When the pattern becomes stationary with the synchronising control turned off, the time base frequency is equal to that of the mains if one complete cycle appears on the screen, while it is half the mains frequency if two cycles are visible, and so on. Next, the synchronising knob should be operated, causing the pattern to " lock " when it is only drifting slowly across the screen, showing that the sweep frequency is nearly equal to that of the mains or to a sub-multiple of it. Again the synchronising control should be used with moderation, the sweep being first brought close to synchronism. Excessive locking effect may cause distortion of the pattern.

Having carried out the procedure just described, the operator will be in a position to make any of the tests that have been mentioned in earlier chapters, with the assistance of the special information provided in those chapters. There are a few general precautions that may be mentioned in conclusion, largely based upon the great sensitivity of the instrument. Since the deflections are due to the creation of electrostatic or electromagnetic fields, it necessarily follows that any external flux that is able to reach the beam will produce a spurious deflection. Although the metal case is an adequate shield against the electrostatic fields, it is impracticable to guard against all possible electromagnetic fluxes without increasing the weight of the set to a prohibitive extent ; and care should therefore be taken not to use it in the vicinity of power or metering transformers, reactors, electrical machines, magnets, or any other apparatus developing more than a very weak external field. Further, a stray field should always be suspected if an unexpected wave-shape makes its appearance.

The question of safety to the operator has been touched upon in connection with several tests ; but it is not always realised that the oscillograph itself employs a voltage that may become highly dangerous if switched on when the case is removed. This procedure should therefore be avoided.

When the trace has to be viewed in a comparatively strong light, the beam can be made more visible by placing in front of the screen a filter of the same colour as the spot. Since reflected light will then have to pass through the filter twice, it will be dimmed more than the fluorescence, which has only to pass once, and then through a filter of its own colour.

Photographic recording has been mentioned frequently, and details given as to methods and technique. An ordinary focussing camera may be used to photograph the screen, or one specially designed for use with the oscillograph, such as that described on pp. 18–19 or p. 176. The effect of screen colour on exposure has been dealt with on p. 17. For the majority of records, ordinary 3¼ in. × 2¼ in. ortho films are suitable, and there is no need to employ the more expensive " chrome " type. A photographic enlargement of five or six times is easily possible without using any special film, or other developer than the standard metol-quinol formula ; but fine-grain developers are available when higher magnifications up to ten or twelve times are desired. Contrasty bromide paper is usually quite satisfactory for prints. Most of the oscillograms used to illustrate this book, for example, were enlarged on to commercial glossy postcards.

The only really difficult problems in connection with photographic recording occur when a single-sweep high-speed trace on the screen of a glass oscillograph tube has to be taken. According to normal camera practice, the image has perforce to be very greatly under-exposed, and it is necessary to strain optical and chemical resources to the utmost in order to secure any readable impression.

Messrs. Nethercot and Beattie (E.R.A.), in conjunction with the Research Laboratory of Messrs. Kodak Ltd., have carried out some very successful work on this subject,[*] and the high-speed oscillograms shown in Figs. 107, 109 and 126, in which they put their methods into practice, indicate the very sensitive results these can achieve, when accompanied by clean and careful manipulation. Their recommendations are included in the following particulars.

(*a*) Oscillograph screen—blue (calcium tungstate).

(*b*) Lens—one of the 35 mm. ciné type, with an aperture of f/1·9, or less. The author uses one working at f/1·3, the cost of which was, however, £65 (in 1936) as against about £10 10*s*. for f/1·9. It should be remembered that the exposure required varies as the square of the f number. A focal length of about 2 in. is advisable.

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[*] See " The Photography of High Speed Transient Phenomena," *J. Sci. Insts.*, Vol. 20, May, 1943, p. 75.

(*c*) Films—glass, celluloid and paper are used as the support material for oscillograph work, but the term " film " will be employed to cover all types. Special attention is now given to scientific requirements by the leading makers of photographic material, and two pamphlets issued by them, viz., " Photography as an Aid to Scientific Work " (Ilford Ltd.), and " Kodak Recording Materials " (Kodak Ltd.), give a great deal of information that is invaluable when difficult work has to be done.

The best kind of film to use depends on the colour of the trace. For a blue screen (calcium tungstate), there is no advantage to be gained by employing a panchromatic emulsion, which would, however, usually improve matters considerably for a green trace (*e.g.*, Willemite), and would do so radically for red (zinc phosphate). The films recommended for the various screens are given in the following table :—

| Make | Blue Screen | | | Green Screen | | | Red Screen | |
|---|---|---|---|---|---|---|---|---|
| | Glass | Celluloid | Paper | Glass | Celluloid | Paper | Glass | Celluloid |
| Ilford | Zenith | 5 B51<br>5 B42 | B.P. 1 | F. P. 3 | 5 G91<br>5 R101<br>8 R101 | B.P. 1 | F.P. 3 | 5 R101<br>8 R101 |
| Kodak | — | R. 35<br>R. 55 | R.P. 30 | | R. 35<br>R. 55<br>R. 60 | — | — | R. 60 |

In the Ilford series, B, G and R signify blue, green and red sensitive respectively, the initial numeral represents the thickness in mils, and the first part of the final numeral (one or two digits) gives the relative speed to *half-watt* light ; 10 being twice as fast as 9, four times as fast as 8, and so on. The Kodak films increase in speed with the code numbers, but R35 and R50 are orthochromatic (green sensitive) and R60 is panchromatic. Of these the second gives a specially high contrast, and is recommended for drum processing. Messrs. Nethercot and Beattie recommend Ilford 5G91 and Kodak Ortho X, the latter of which is not included in the Table, but is almost identical with the present R55. Glass plates should be backed.

(*d*) Development—the most suitable developer is metal-hydroquinone, containing a relatively large amount of potassium bromide to secure contrast. Suitable developers in the ready-made-up form are ID-33 (Ilford) and D.163 (Kodak). Development time should not exceed 5 minutes at 65° F. ; while when intensification is to follow, it is so important to avoid background fog that 4 minutes is safer, since the intensifier also deepens the fog.

Intensifier—the faint image produced by development can be greatly strengthened by intensification. Messrs. Nethercot and Beattie recommend the uranium formula as supreme for this work. In addition to very great intensification, it is a single-stage method and is hence less liable to mishap than, for example, mercuric chloride; and, further, the process can be stopped at any time, when the density is considered sufficient. The Kodak formula (IN–21) is as follows:—

| *Solution A* | | *Solution B* | |
|---|---|---|---|
| Uranium nitrate . | 20 grm. | Potassium ferricyanide | 20 grm. |
| Acetic acid (glacial) . | 10 c.c. | Water, to make . | 500 c.c. |
| Water to make . | 500 c.c. | | |

Use 1 part of A, 1 of B, and 6 of water. Thoroughly wash after fixing and do not prolong intensification for more than three minutes. The final washing must not exceed a few minutes.

(*e*) Printing—very contrasty glossy paper should be used, such as Ilford B61K or Kodak BG4 and 5, and a " contrast " developer. The use of a condenser type enlarger always gives more contrast than contact printing. A yellow filter may also help towards the same end.

METAL-TUBE TYPE. What has been said with regard to the glass tube oscillograph applies also in the case of the metal pattern, allowance being made for the distinctive features of the two instruments. Thus a repeating time base would not in general be used for continuously evacuated tubes, the main purpose of which is to secure the utmost sensitivity for photographic recording; its place being taken by the rotating film or the single sweep base. A full description of a typical model has been given in Chapter II on p. 8, and of other models on pp. 66 and 67, from which the differences in the methods of adjustment will already have been gathered.

The two chief changes are with regard to evacuation and photography, including the dehydration of the celluloid film. Estimation of the vacuum has been described on p. 28, and film-drying in a vacuum desiccator on p. 134. Small films, however, such as 6- or 12-exposure spools, can be allowed to dry out in the oscillograph, as the quantity of moisture is not sufficient to lengthen the pumping process to an inconvenient extent.

Photographic material for insertion in the vacuum may be quite slow (*e.g.*, H. & D. 20), as the electrons do not penetrate more than the surface layer, and there is no appreciable gain in employing a more sensitive emulsion. The development of a 2-metre length may be carried out by suspending it, doubled round a roller-weight at the bottom, in a narrow tank about 4 ft. tall ; or by arranging it to rotate on a drum or round two rollers, the lower part of which is immersed in a small dish of solution. Variants of these methods are known in connection with the processing of cinema films.

**Maintenance.** GLASS TUBES. As with radio receivers, cathode ray oscillographs are now so reliable that practically no special maintenance, in the usual sense of the word, is required. There is no part that requires lubrication or other periodic attention ; and provided reasonable treatment is accorded them, they can be expected to function for long periods without trouble, until one or more of the components actually reaches the end of its normal life. Replacement of the worn-out part is then indicated.

Years ago it was not unknown for a radio receiver to fail prematurely owing to one of the valves " going soft," *i.e.*, partly or wholly losing its vacuum ; and the same could have occurred with the cathode ray tube. Such an event is very rare indeed with the improved manufacturing methods in use to-day. All tubes in common use can be relied upon to continue in use for over 1,000 hours without showing any appreciable deterioration ; and this period represents a number of years of working life.

The gas-focussed tube is an exception to the usual long-life rule. On account of the relatively quick deterioration of its cathode, it will need replacement after only a few hundred hours of service. During this period, the focus may need correction at long intervals by the reduction of the filament series resistance, which may be effected, when no other provision for adjustment is made, by pulling out a turn of the resistance wire and resoldering.

Variable resistors possess practically the only rubbing parts in the whole assembly. The higher the resistance the less robust these are likely to be, and occasionally one of them may give uneven action through wear. The nature of the attention required will depend on the design, but is not generally a difficult matter.

METAL TUBES. Very little maintenance is also needed by the metal tube oscillograph. If the joints are carefully made as described earlier in the chapter, the creation and retention of the vacuum will continue to be effected with uniform facility for an indefinite time. If not, the faulty joint should be remade in accordance with the instructions.

The vacuum pumps are simple to operate ; any special requirements would be covered by brief instructions issued by the makers. If mercury diffusion pumps are used, a mercury vapour " trap " will be fitted between the pumps and the tube, consisting of a jacket round the exhaust pipe packed before operation with a freezing mixture consisting of $CO_2$ " snow " and ether. The solid $CO_2$ may be stored for relatively long periods in a wooden box lined with a 3-in. thickness of a heat-insulating medium such as hair-felt or granulated cork. Water vapour is also trapped by the device.

This complication is absent when oil diffusion pumps are fitted. The oil lasts indefinitely if care be taken to keep it out of contact with the atmosphere while it is in the heated condition.

The only part of the whole apparatus that is subject to wear is the cold cathode, the flat end of which gradually becomes pitted to form a small crater. When this has gone too far, the beam is liable to become unsteady through change in focus and direction. It is therefore necessary to remove the discharge tube and clean up the cathode every few months.

Since the fluorescent screen is a simple and cheap component, and is, moreover, easily renewed, there is not the same need to safeguard it from burning ; while there is also not the same need for a bright spot as with the glass tube, since the screen is not used for photographic recording.

# APPENDIX

## A. CHARACTERISTICS OF THERMIONIC VALVES

Thermionic valves are much used as accessories in a cathode ray set, five or six being quite often fitted inside the case of a glass tube oscillograph. The term by which they are known in this country is a very appropriate one, as they are able to provide the exact electronic analogy of any type of mechanical valve, including the non-return, throttle, and safety-valve patterns. It is the author's opinion that they will secure a much extended use in the future for building up new devices forming the electrical equivalents of useful mechanical apparatus.*

**Two-electrode Valve, or Diode.** The simplest type is that having two electrodes sealed into an evacuated glass bulb. This is the original form produced by Fleming in 1904 as a result of a research based upon the behaviour of a carbon-filament lamp. Of the two electrodes, the cathode consists of a short filament directly heated by a current, or of a thin rod wound with an insulated heater coil. The anode is a broad strip of metal, usually in the form of a cylinder surrounding the cathode, and is often called the " plate." Electrons are given off from the hot electrode at a rate depending on the temperature, and hence on the watts applied to the filament or heater ; and will flow from the cathode to the anode if an " accelerating " voltage of quite a low value is applied between them. This voltage must be at least sufficient to overcome the natural attraction between the (negative) electrons and the positive ions left on the cathode, and must naturally be so connected that the " plate " is positive relatively to the filament. The stream of electrons constitutes an electric current, its circuit being completed through the H.T. battery or D.C. power supply.

The above characteristic performance is shown by the curves in Fig. 185, which indicate the current in milliamps. flowing for various anode voltages. For example, if the second lowest curve be considered, for which the cathode is heated by a power of 1·7 watts, the anode current rises almost linearly with the voltage until the latter has reached 4 volts, at which the anode current is about 3 mA. But after this point the supply of electrons due to the hot cathode, forming a " space charge " in the vicinity of the cathode, is not sufficient to enable the proportionate rate of current increase to continue, and the curve bends over. Finally, at a voltage of about 30 no further increase of current can take place, and the curve becomes horizontal at about 6·2 mA.

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* See for example Bowdler, " Measurements on Impulse Voltages with a Ballistic Galvanometer," *Jnl. I.E.E.*, May, 1942, Vol. 89, p. 237.

In this condition the diode is said to be " saturated," and in order to secure a higher current, more electrons must be forced out of the cathode by raising its temperature. The remaining curves illustrate the effect of increasing or decreasing the wattage by the small amounts indicated on the curves, which it should be noted are characteristic of tungsten or thoriated tungsten filaments.

If the voltage applied across the electrodes be reversed, no current at all will flow, as the space charge is simply attracted into the cathode, and the diode thus acts as a perfect non-return valve. Hence it is much used to rectify the applied A.C. in power units for giving a D.C. supply to a radio receiver or cathode oscillograph. The curves also illustrate how a saturated diode functions as a constant current device, for example when forming part of a linear time base. The principles described above are of great importance, as they form the basis of thermionic valve action generally, including that of the hot cathode oscillograph tube.

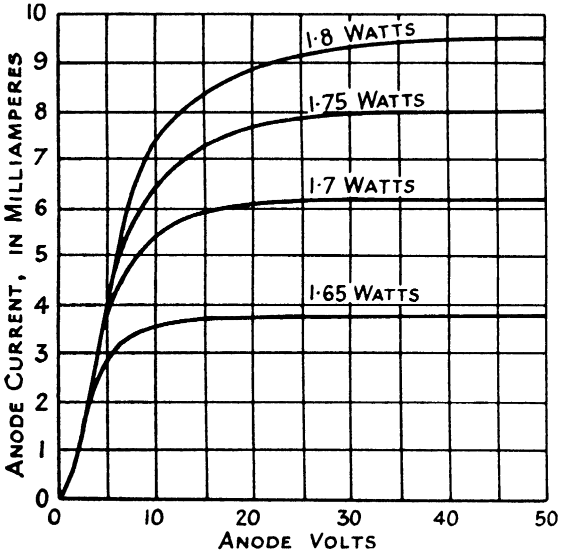

Fig. 185.—Characteristics of diode valve with tungsten filament, at various filament wattages.

**Three-electrode Valve, or Triode.** If a third and perforated electrode in the form of a wire gauze or " grid " construction be interposed between the other two, and a controlled voltage applied to it, the anode voltage being maintained constant, the amount of space-charge propelled towards the anode, *i.e.*, the anode current, now depends on the grid voltage ; or in other words the control of the current delivered is taken over by the grid, the characteristic curve, however, retaining much the same shape. The triode is thus the electronic equivalent of the mechanical stop-valve or throttle-valve, or engine governor when the regulation is carried out automatically.

Its performance is indicated in the Grid Volts/Anode current curve in Fig. 186. One advantage of the three-electrode principle is that the anode current is now produced by a constant anode voltage ; and a second is that by adjusting the basic voltage about which the grid voltage alternates, *i.e.*, the grid bias, the whole of the straight part of the characteristic can be employed. Thus an undistorted anode current wave can be produced corresponding to an impressed grid-voltage wave ; and by passing the anode current through a resistance, a voltage-drop measured by IR is developed across it which is many times the applied grid voltage, and amplification has thus been effected.

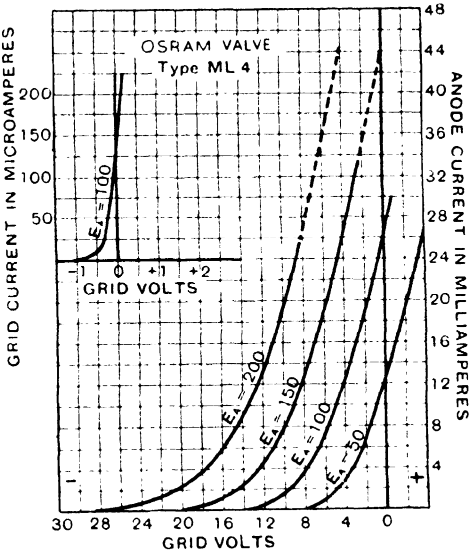

FIG. 186.—Characteristic curve of typical triode valve.

As valves are designed for many different functions, various parameters are employed to enable their capabilities to be specified or measured. The first of these expresses the change of anode current that can be produced by a given change in grid voltage. Now a voltage divided by a current gives a resistance, and conversely the ratio between a current and a voltage is a conductance, which in this particular case is termed the " mutual conductance " of the valve, since its value depends upon the mutual relationships between the two electrodes, such as their spacing.

Another value that is required is the " amplification factor," or the ratio of the change of anode voltage to the change of grid voltage, at constant anode current. The " impedance " or A.C. resistance is the reciprocal of the mutual conductance multiplied by the above factor ; or the amplification factor divided by the mutual conductance. These various particulars all enable a valve to be selected for a given function and to be co-ordinated with the other components in its circuit, in much the same way as, for example, the particulars of a transformer or even a machine are employed in power engineering.

Their derivation may be exemplified from the characteristics in Fig. 186. If the $E_A = 150$ volts curve be taken, it will be seen that a change in grid voltage from 0 to $-6$ causes a change in anode current from 44 to 19 mA, or 25 mA. The mutual conductance is therefore 25/6, or 4·2 mA per volt. The amplification factor may be arrived at by measuring the effect of varying the grid voltage upon the anode voltage at constant anode current. A current of 20 mA is given by the 200 $E_A$ curve at a grid voltage of $-9{\cdot}8$ ; and by the 150 $E_A$ curve at one of $-5{\cdot}65$. Hence a change of 50 volts on the anode corresponds to a change of 4·15 volts on the grid, giving an amplification factor of 50/4·15, or 12. Finally, the impedance is 12/·0042, or 2,860 ohms.

In screen-grid and pentode valves, other grids are inserted alongside the control grid, chiefly for the purpose of greatly reducing capacity coupling between the latter and the anode, and so increasing the duty and efficiency of the valve.

**Gas-filled Valves.** The above tubes have a high vacuum, and are hence termed " hard " valves. In the early days of valve manufacture, the vacuum was liable to deterioration through the release of occluded air from the glass or electrodes. Collisions occurred between the intrusive molecules and the electrons, forming positive ions, which partly neutralised the electrons in the space charge and so impaired the performance. Such valves were said to have " gone soft."

When, however, a relatively large quantity of gas is introduced intentionally, the above action is enhanced and serves a useful purpose. As the voltage between the electrodes rises, the space charge is neutralised at quite a low value of voltage. The current then jumps to its full cathode emission value, which is reached in the case of the tube containing mercury vapour at only about 15 volts. Gas-filled diodes are hence frequently used in rectifying circuits, where the gain in efficiency may confer a decided advantage.

In the case of a gas-filled triode, a reduction in the negative grid bias is able to produce quite suddenly the full cathode emission current at an anode voltage of about the above value ; and after this has happened, the grid exercises no further control and the plate current persists at its existing maximum value. An extremely useful characteristic is thus provided, the gas-filled triode constituting an electronic switch or relay. Under the names of the " gas-filled relay " or " thyratron," it is much used for high-speed triggering of control circuits. Its use for initiating the sweeps of a repeating time-base has been described in Chapter III ; while its ability to inaugurate a square-fronted wave has enabled it to form the basis of the recurrent surge generator and the restriking voltage indicator described in Chapter IV.

A time-lag of about $10^{-5}$ seconds is introduced by the ionising process, which as mentioned in connection with time-bases may be a disadvantage.

## B. PHOTO-CELLS

Light-sensitive devices have been responsible for some of the most recent developments of control engineering, as well as of sound reproduction and optical determinations. In themselves these apparatus are not altogether new, but they have been endowed with new possibilities by the perfecting of the thermionic amplifier, and on account of their new utility they have been rapidly improved and their types increased in number and variety. So recent has been this major development that many engineers are as yet unfamiliar with their various characteristics, and the author proposes to give a short summary of their chief forms, mode of operation, and uses.

There are three main types of photo-cell :

(*a*) Photo-conductive cells, which have the property of changing their resistance when the amount or quality of light falling upon them varies.

(*b*) Photo-electric cells, which resemble thermionic diode valves in that they consist of an evacuated tube containing an anode and a cathode between which must be connected a H.T. voltage supply. Then light impinging on the cathode causes a current to flow proportional to the light intensity.

(*c*) Photo-voltaic cells, which are coated metal plates that actually develop a voltage and pass a current when light strikes them, the voltaic energy produced being sufficient to operate a sensitive meter or relay.

It will be seen that the last is the only type that generates its own power, and also that the characteristics of the three are sufficiently diverse to enable a wide range of functions to be closely met. A brief summary of their special features will therefore be given.

(*a*) **Photo-conductive Cells.** The basis of the photo-conductive cells used in practice is the metal selenium. This exists in a number of allotropic forms, but any of the others can be converted into the metallic by heating at 200° to 220° C. It is thus easy to produce a film of active metal by spreading a layer of amorphous selenium upon a suitable support, such as ground glass or another metal, and applying heat. As its resistivity is extremely high, the process of forming the cell usually consists of dividing a surface or thin sheet of some suitable metal into two interlacing " grids," and then coating the selenium film over the whole so as to join the two portions together by a connection having a very short length but a relatively great width.

Then the result of exposure to light is to reduce the resistance considerably, *e.g.*, from, say, 5 to 1 megohm for an intensity of 5 foot-candles. The variation is not in linear, but in exponential proportion to the light intensity, the relation being—

$$1/r_1 - 1/r_0 = gF^x,$$

where $r_1$ is the " light " resistance, $r_0$ the " dark " resistance, F the light flux, g the cell constant and x a constant very near to 0·5. Thus the photo-electric current varies very nearly as the square root of the illumination.

There is a definite time-lag between cause and effect which unsuits the cell for television and similar purposes. It was, however, used even prior to the coming of thermionic amplifiers for photometric purposes ; as the basis of the " Optophone," a very successful apparatus for enabling the blind to read ordinary print by translating the letters into a succession of musical chords ; for receiving telegraphy or telephony transmitted along light waves ; and for other purposes. Assisted by modern amplification, its utility has been greatly extended. For sound films, which require distortionless reproduction up to 10,000 cycles per second, it was at first employed, but has now been superseded by the photo-electric cell on account of its partial suppression of sibilants and other high-frequency consonants.

(*b*) **Photo-electric Cells.** The metals of the alkaline groups have the property of emitting electrons when visible light falls upon them. When an evacuated tube contains a surface coated with one of these, forming the cathode, and a ring-shaped electrode in the path of the light as the anode, variations of illumination will enable a voltage of, say, 90 volts to pass a current of some micro-amperes, varying linearly with the light intensity. Although the output is very small, the action is instantaneous, and the voltage is high enough for efficient thermionic amplification. This forms an ideal cell for television and talking-picture work.

The introduction of a residual trace of helium or other inert gas considerably increases the output, but introduces a time-lag sufficient to put the cell out of court for television, which involves frequencies up to $10^6$ c/s.

Great improvements have been made in the photo-electric type as a result of continued research with different cathode materials, and the advance is still in progress. The best material depends to a large extent on the colour of the light ; sodium, for example, being at an advantage for ultra-violet light and potassium for visible violet. One of the most sensitive coatings for white light is a combination of cæsium oxide and silver containing free cæsium, all coated with an extremely thin layer of pure cæsium.

This type of photo-cell is the most generally useful. It combines well with the valve amplifier, and its VA output, though small, is yet well above the noise level introduced by the amplifiers themselves. Its applications are many and are steadily increasing. They include not only television and talking pictures, but also visual testing apparatus, smoke detection and measurement, traffic signalling by registering the approach of vehicles and other road users, self-opening of doors, electronic organs, and many cases of industrial control, in which the photo-cell detects the passing of the work or the motion of part of a machine or engine.

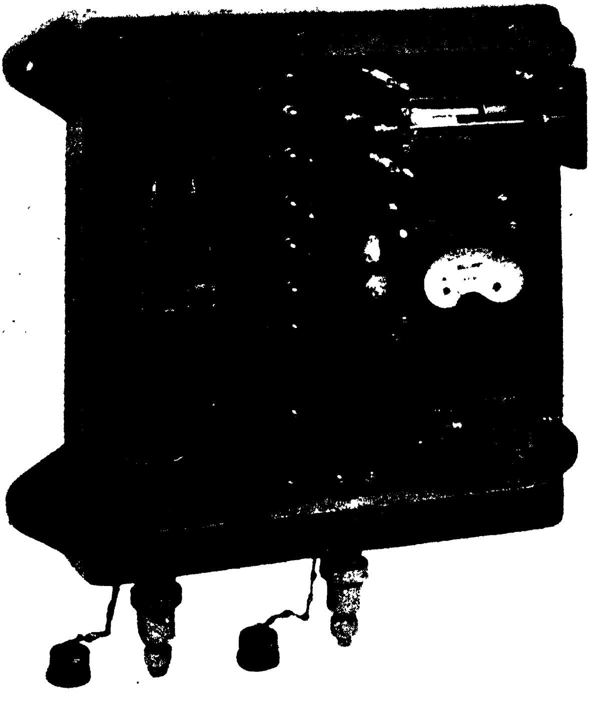

FIG. 187.—Photo-electric cell installation including Osram CMG 8 cell in right-hand top corner (Witton-Kramer).

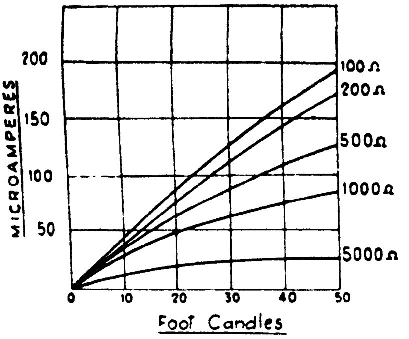

FIG. 188.—Average current output for various load resistances of Salford No. 1 photo-voltaic cell.

A typical photo-cell installation by Messrs. Witton Kramer, suitable for practically any of these purposes, is shown in Fig. 187, comprising the Osram C.M.G.8 cell itself in the right-hand top corner, a milliammeter, sensitive relay, and resistors on the left. The beam of light from the projector lamp would strike vertically downwards, *i.e.*, parallel to the paper, through the glass bulb of the cell, upon the trough-shaped cathode placed horizontally inside the vacuum.

(*c*) **Photo-voltaic Cells.** The most recent type of photo-cell is also the simplest in both construction and use. It consists of a relatively thin metallic plate, typical dimensions being 40 mm. (1·58 in.) × 22 mm. (0·87 in.) × about $\frac{1}{16}$ in. thick, the flat surface being specially prepared. In one form, first produced about 15 years ago, a copper plate has one surface coated with copper oxide, with a very thin layer of platinum or gold sputtered over this to provide the return circuit. Recently, however, selenium has been substituted for the copper ; and for the small size mentioned above, has proved capable of giving currents up to 200 micro-amps. or over in response to an illumination of 50 foot-candles. This is several times the current output of a typical vacuum photo-electric cell.

A distinguishing feature is the relatively low internal resistance, viz., about 300 to 2,000 ohms. This is high enough to render long leads practicable from the cell to the measuring micro-ammeter, but not high enough to enable the cell to operate thermionic amplifiers. The operating characteristics with various light-intensities and load resistances are shown in Fig. 188. The output varies linearly with the intensity.

The great advantage of this type of cell is that not only is no battery or other external supply of energy necessary as with the other two, but the output is sufficient to operate a small portable instrument. Consequently

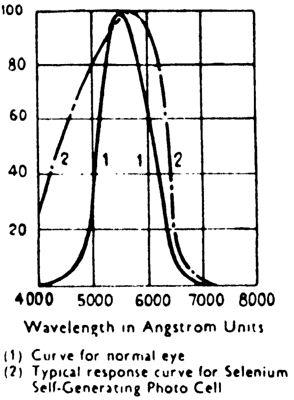

FIG. 189.—Comparison between colour sensitivity of human eye and Salford selenium photo-voltaic cell.

it has come greatly into use for portable and pocket photometers, illumination meters, and photographic-exposure meters. The action is purely electronic, being due to the " barrier-layer," which permits electrons under the influence of light to leave the semi-conducting surface for the adjacent metal ; but not to return. Since there is no chemical action, the cells are practically everlasting, and are actually very robust. Finally, its colour sensitivity is very similar to that of the human eye, as is shown in Fig. 189 ; and this property is the basis of the Photo-electric Colorimeter in which it is the principal component.

Recent instruments embodying the photo-voltaic cell are the Comparative Glossmeter and the Transparency Comparator.

## C. OSCILLATORS

An oscillator is a valve circuit for generating electrical waves of accurately calibrated frequency. It therefore resembles a simple transmitting set, or even a radio receiver in which the excessive use of reaction has caused the detector valve to oscillate and thus function as a transmitter. Feed-back is hence a feature of the apparatus.

There are many variants of the " detector " type of circuit which may form the basis of an oscillator. One, the tuned-anode/tuned-grid circuit, has already been employed in Chapter V and illustrated in Fig. 60 ; and there are others simpler or more complex than this. It is, of course, necessary that the tuning dial shall be calibrated in cycles (or kilocycles) per second.

For frequencies below about 10 kc/s, the components of a " straight " oscillator, such as that mentioned above, become somewhat cumbersome, and a heterodyne circuit, containing two valves producing a beat frequency, is commonly employed for this range, providing values down to about 20 c/s.

## D. PIEZO-CRYSTALS

The piezo-electric effect was mentioned in connection with its application to frequency regulation in Chapter VI and to pressure measurement in Chapter IX, the actions in the two cases being the converse of each other. Crystals belonging to the hexagonal system (and also certain pseudo-hexagonal members of the monoclinic system, such as dextrose) exhibit the effect, the best known being Rochelle salt, tourmaline and quartz, of which the last is that most frequently employed for instrument work. It will therefore more particularly be described as the typical member of its class.

Quartz crystallises in the form of hexagonal prisms, as shown by the plan and oblique view in Fig. 190, each end being terminated by a hexagonal pyramid (as in the small figure) when the crystal is complete; but since the pyramids are removed at the start of the cutting operation, they are omitted in the main figure. The vertical centre-line forms the " optical " axis, and a horizontal line passing through any two opposite angles of the hexagon would form an " electrical " or " diagonal " axis. Then the " mechanical " or " third " axis passes through the intersection of the above pair and is at right angles to each of them, as shown. Any lamination cut parallel to the optical and mechanical axes, as exemplified by the cross-hatched section, will give the performance described in Chapter IX.

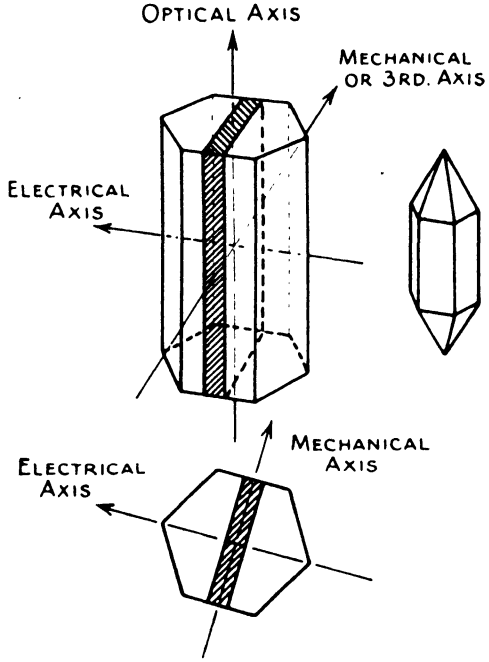

FIG. 190.—Diagram of piezo-crystal.

Since this action is reversible, it may be restated as the production of electric charges upon faces at either end of the electrical axis when a mechanical pressure is applied along that axis; or conversely the production of a mechanical force along the electrical axis when a potential is applied at the ends of that axis. In each case pressure and voltage vary linearly with each other; and it should be understood that the term " axis " as applied to a plate designates a direction and not an actual line.

Quartz has the great advantage of robustness, its crushing strength being about 50,000 lb. per sq. in. As it occurs freely in nature, it is completely stable, and can readily be obtained in large and flawless crystals. Plates intended for use in oscillators are cut into circular discs, and they then vibrate mechanically as diaphragms when an alternating voltage is applied at the ends of their electrical axis. Since such a vibrating part is electrically equivalent to a tuned circuit consisting of a capacitance and an inductance in parallel, it may be connected to the grid and cathode of a thermionic valve instead of the orthodox tuning combination, and will then compel the valve to oscillate in accordance with its own natural frequency. The crystal possesses a negative temperature characteristic of only about 20 parts in a million per 1° C., and thus forms a very constant regulator for keeping the frequency at an exact standard value. During the last few years, special plates have been developed, mainly by altering the angle of cut, which commonly have a temperature coefficient of only 1 or 2 parts in a million per 1° C. For very special purposes, moreover, plates can be made having coefficients as low as 1 part in $10^8$ per 1° C.

The use of the crystal for converting pressure into voltage has been fully described in Chapter IX ; while it figures in the radiolocation type of flow-detector in Chapter VII for converting radio oscillations into supersonic ones and *vice versa.*

## E. LECTURE DEMONSTRATION SET FOR THE CATHODE RAY OSCILLOGRAPH

A lecturer or experimenter who wishes to carry out a set of typical tests in order to demonstrate the applications of the cathode ray oscillograph may have to transport a considerable quantity of apparatus, much of it delicate, spend a long time before and during the demonstration in connecting it up, and run the risk of a failure to operate through a faulty connection or component when the critical moment has arrived. The author was recently under this necessity, and after a preliminary trial with loose gear loaded for transit in a couple of packing-cases, adopted a compact assembly designed by Mr. G. L. G. Jeans for carrying out about a dozen sufficiently spectacular tests in quick succession. Of the many physicists and engineers who are interested in the instrument there are probably a number of teachers, students, and amateurs who may be glad to have particulars of the circuits and apparatus suitable for such a demonstration, and it is therefore thought worthy of a brief description.

## Requirements

The chief requirements are as follows :—

1. The equipment must provide for the carrying out of a really interesting series of tests, covering a wide range of physical and engineering measurements.
2. The whole must be as far as possible fixed in place in a container of the " Suit-case " type, not too bulky or heavy to be readily carried in one hand.
3. Connections must be quickly changeable from one test to the next, so that the whole series can be completed in from 20 to 30 minutes.
4. The possibility of a breakage or mistake must be reduced to a minimum.
5. No critical adjustments must be required.
6. The cost must be low.

## Tests

The following list of tests was drawn up, as combining the two requirements of instruction and entertainment :—

(*a*) Putting the instrument into commission, and showing the effect of the various controls.

(*b*) An A.C. wave.

(*c*) Transients due to breaking of inductive circuit.

(*d*) " Saw-tooth " wave produced by striking of neon tube.

(*e*) Fluctuations of light.

(*f*) Frequency comparison by Lissajous' figure.

(*g*) B/H curves of typical iron specimens.

(*h*) $I_A/E_A$, characteristics of typical thermionic valves, showing effect of varying grid bias.

(*i*) Wave shape of typical musical sounds.

## Design of Apparatus

The completed apparatus is shown in the photographs in Figs. 191 and 192, from which, with the aid of the key diagram forming Fig. 193, the various components can be made out. There is no need to refer to the position of each item, as the diagram gives their identity. The dimensions of the case, which is made of ½ in. plywood, are 20 in. × 15 in. × 6 in. A few notes as to the apparatus functioning in each test are however required.

Tests (*a*) and (*b*) do not need any gear outside the oscillograph ; the A.C. wave in (*b*) being derived from the mains voltage *via* the power unit transformer.

The inductive circuit and its rupture (*c*) are provided by an ordinary

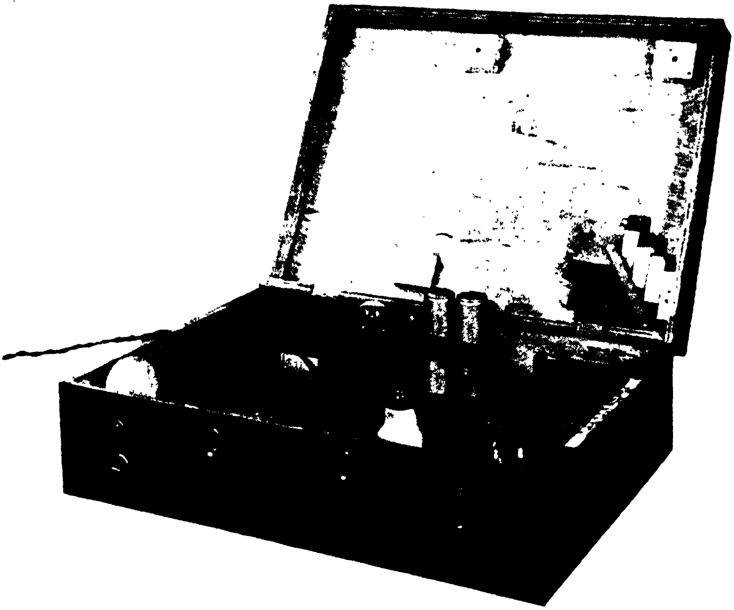

FIG. 191.—Side view of " suit-case."

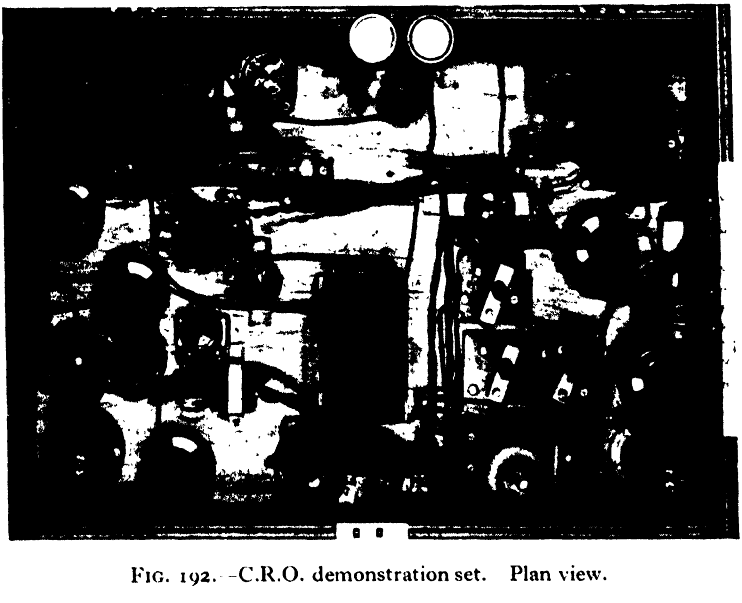

FIG. 192.—C.R.O. demonstration set. Plan view.

trembler bell F without its gong. As shown in Fig. 94, the switching transients are quite typical, the device being in effect a circuit breaker on a small scale.

Quite a small neon lamp J can be used for (*d*). By connecting it across a condenser charged through a series resistance, an interesting example of a transient is provided (see Fig. 27), while the circuit illustrates graphically the triggering of a repeating time base.

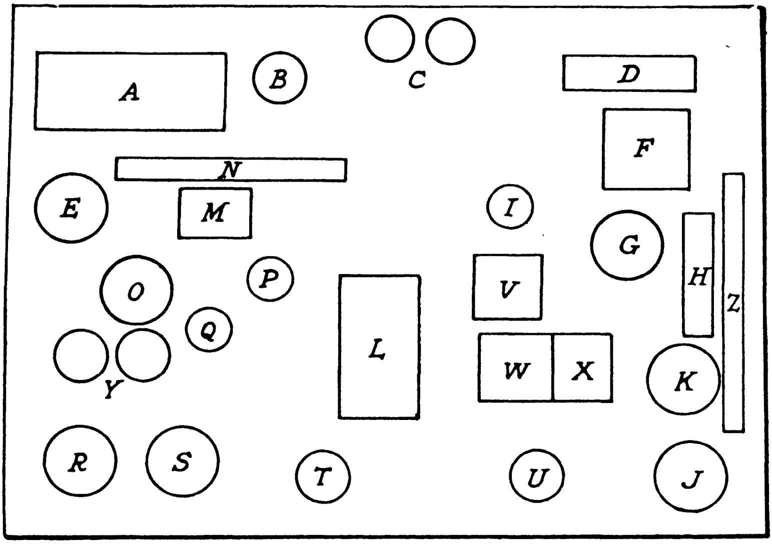

FIG. 193—Demonstration set. Key diagram.

A, Main transformer. B, Rectifier valve. C, Smoothing condensers. D, Smoothing choke. E, Switch for mains transformer. F, Electric bell. G, Switch for electric bell. H, Battery for electric bell. I, Voltage adjusting potentiometer for neon lamp. J, Neon lamp. K, Switch for neon lamp. L, Coils for B/H test. M, Integrating condensers for B/H test. N, Limiting resistance for B/H coil. O, Mains switch for B/H coil. P, Phase adjusting resistance for B/H coil. Q, Phase adjusting resistance for Lissajous' figure. R, Lamp. S, Lamp switch. T, Photo-electric cell. U, Pentode for valve characteristics. V, Triode-tetrode switch. W, Tetrode-pentode switch. X, Grid-bias selecting switch. Y, Mains sockets for cathode-ray oscillographs. Z, Sockets for C.R.O. deflector-plate connections

For (*e*), the fluctuating light is furnished by an incandescent lamp R fed from the A.C. mains. A photo-electric cell T picks up some of this light and delivers what seems at first sight to be an A.C. voltage of double mains frequency ; but by intercepting the light with the hand or a card, it can be shown to be the ripple on a D.C. voltage ; and also the self-centring action of the screen image will be demonstrated.

To produce Lissajous' figures of varying ratios for (*f*) would require the provision of some kind of oscillator, and the author has used a small variable speed rotary machine for the purpose. This however introduces more complication than is justified, and a much simpler method of forming a single figure was adopted by taking advantage of the double-frequency wave from the photo-cell. A 2 : 1 figure is so obtained without the need for any adjustment ; and by varying the phase-angle of the 50 c/s voltage through 90° by means of a condenser and variable resistance, all forms of the figure from the U-shape to the figure 8 can be shown.

Two coils are needed for the B/H determination (*g*), one for magnetising the specimen and the other for recording the flux density, and these can for demonstration purposes be wound concentrically as in L. The simplest method of introducing the specimens is by making each in the form of two L-shaped laminated cores, which join up to form a complete rectangular iron circuit after one has been threaded through the winding. Suitable specimens are mild steel, stalloy and mumetal ; two pairs are seen clipped to the lid of the case for transport in Fig. 192. The straight-line figure seen in the screen with no specimen in position may be described as the B/H curve for air.

Characteristics of the triode, tetrode and pentode can be obtained in (*h*) from the one pentode valve U by putting the unwanted grids out of action in turn.

Finally the sound records for (*i*) were made with the help of a hand microphone having a self-contained 3 V dry battery. The simplest plan is to arrange that the various instruments produce the same note or pitch, so that the time-base can be tuned at the outset to give stationary figures for all. Suitable sounds are those from a tin trumpet, a tin whistle or recorder, the human whistle in two octaves, and the human voice singing the same two octaves and a falsetto version of the upper one. The lower octave should be sung to various vowels. Other sounds will readily suggest themselves.

## Circuit Details

A diagram of all connections is given in Fig. 194 ; the terminals on the right and at the bottom being plug-in sockets for rapidly connecting the X or Y plates, or the common lead E. Those tests which require a D.C. power-supply obtain it from the " mains unit " shown in the upper left. As each circuit is labelled in the figure, the scheme can readily be made out in every case.

The capacity-resistance combination $C_4R_8C_5$ is a phase-shifting circuit for correcting the phase of the anode voltage in the valve-characteristic test. A switch on either side of the test valve enables the number of grids to be changed. As shown, all grids are in action. For the tetrode, the right-hand switch is moved upwards, connecting the two upper grids together and to 100 V. ; while for the triode, the left-hand switch is now moved down, connecting the same two grids to the

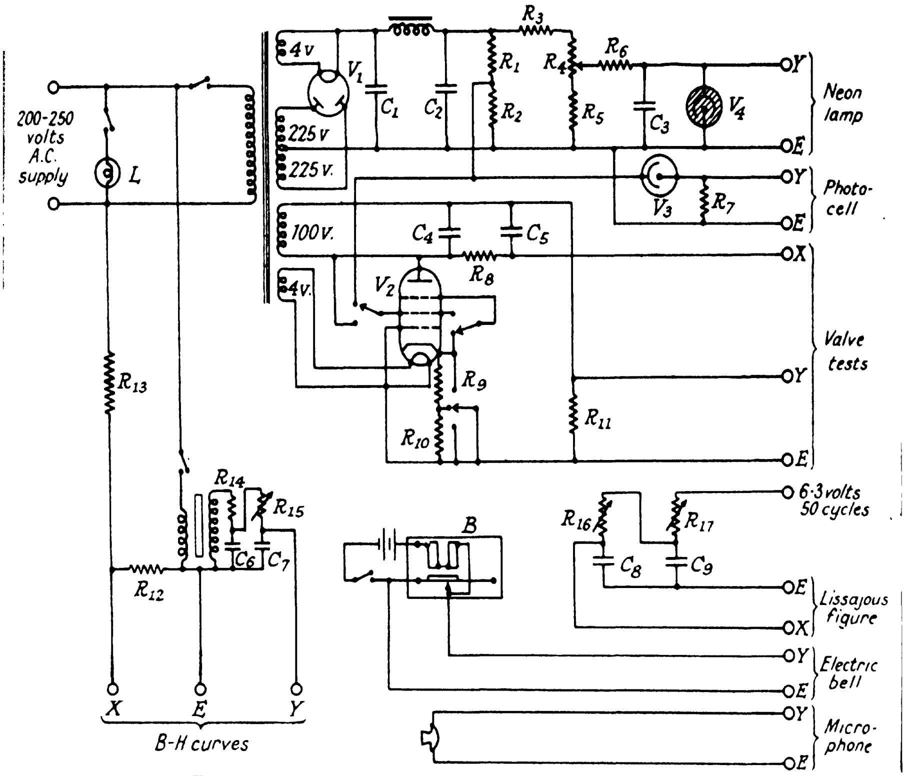

FIG. 194.—Demonstration set, connection diagram with schedule of values.

| | |
|---|---|
| $R_1$ | 60 KΩ |
| $R_2$ | 35 KΩ. |
| $R_3$ | 10 KΩ. |
| $R_4$ | 10 KΩ Potentiometer. |
| $R_5$ | 35 KΩ. |
| $R_6$ | ·25 MΩ. |
| $R_7$ | 1 MΩ. |
| $R_8$ | 75Ω. |
| $R_9$ | 250Ω. |
| $R_{10}$ | 250Ω. |
| $R_{11}$ | 800Ω. |
| $R_{12}$ | 5Ω |
| $R_{13}$ | 115Ω. |
| $R_{14}$ | 12 KΩ. |
| $R_{15}$ | 3 KΩ Potentiometer. |
| $R_{16}$ | 10 KΩ Potentiometer. |
| $R_{17}$ | 47 KΩ Potentiometer. |
| $C_1$ | 8 MF. |
| $C_2$ | 8 MF. |
| $C_3$ | ·05 MF. |
| $C_4$ | ·5 MF. |
| $C_5$ | ·5 MF. |
| $C_6$ | 1 MF. |
| $C_7$ | 1 MF. |
| $C_8$ | ·05 MF. |
| $C_9$ | ·05 MF. |
| $V_1$ | Osram MU.12/14. |
| $V_2$ | Osram MS.P4. |
| $V_3$ | Photocell. |
| $V_4$ | 5 watt Osglim lamp. |
| L | 250 volt 25 watt lamp. |
| B | Electric bell. |

anode. The tapped resistance and 3-way switch below the valve alter the value of grid bias.

The resistance-capacity combination $R_{16}$ $R_{17}$ $C_8$ $C_9$ in the lower-right of the diagram provides a phase shift of up to 90° for the Lissajous' figure ; while the similar combination on the opposite side, $R_{14}$ $R_{15}$ $C_6$ $C_7$, integrates the secondary current of the B/H experiment to convert its reading from the rate-of-change of flux to the plain flux. The potentiometer resistance $R_4$ near the top-middle forms a voltage adjustment for the neon lamp $V_4$. It will be found that the repeated striking of this lamp is rather sensitive to applied voltage.

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